DOCUMENT RESUME

ED 180 841 SE 029 874

TITLE	The Power Transistor: A Module on Heat Transfer. Tech Physics Series.
INSTITUTION	Technical Education Research Center, Cambridge, Mass.
SPONS AGENCY	National Science Foundation, Washington, D.C.
PUB DATE	Nov 72
GRANT	NSF-GY-9317
NOTE	73p.: For related documents, see SE 029 875-876: Contains colored pages which may not reproduce well
EDRS PRICE	MF01/PC03 Plus Postage.
DESCRIPTORS	*Electronics: *Energy Conservation: Heat: Kinetics: Laboratory Procedures: *Learning Modules: *Physics: Postsecondary Education: Science Education: Technology: *Transistors

ABSTRACT

This module is intended to provide an understanding of the principles related to heat transfer. The objectives are designed to enable the learner to select and install a device for measuring the temperature of a power transistor, determine power ratings, measure the transient response for a power level and its final equilibrium temperature. Other objectives include being able to find thermal resistance and the time constant of the system: use thermal resistance, final temperature, and time constant to find heat capacity: find final temperature for any power input and an operating point: find the factors affecting thermal resistance: and lower the thermal resistance to improve dissipation of power. (Author/SA)

****
* Reproductions supplied by EDRS are the best that can be made *
* from the original document. *
****

ED180841

TECH PHYSICS SERIES

U S DEPARTMENT OF HEALTH, EDUCATION & WELFARE
NATIONAL INSTITUTE OF EDUCATION

THIS DOCUMENT HAS BEEN REPRODUCED EXACTLY AS RECEIVED FROM THE PERSON OR ORGANIZATION ORIGINATING IT. POINTS OF VIEW OR OPINIONS STATED DO NOT NECESSARILY REPRESENT OFFICIAL NATIONAL INSTITUTE OF EDUCATION POSITION OR POLICY

"PERMISSION TO REPRODUCE THIS MATERIAL HAS BEEN GRANTED BY
Mary L. Charles
NSF
TO THE EDUCATIONAL RESOURCES INFORMATION CENTER (ERIC)."

THE POWER TRANSISTOR

A MODULE ON HEAT TRANSFER

The materials herein produced at the:

Printed: November, 1972

TERC Curriculum Materials Development Laboratory
575 Technology Square
Cambridge, Massachusetts
02139

TERC Headquarters at:
44 Brattle Street
Cambridge, Mass. 02138

A non-profit public-service corporation

TERC
Technical Education Research Centers

SE 029 874

Copyright, 1971 by the Technical Education Research Center, Inc. Printed in the United States of America. All rights reserved. This book, or parts thereof, may not be reproduced in any form without permission.

Copyright on these materials is claimed only during the period of development, test and evaluation, unless authorization is granted by the National Science Foundation to claim copyright also on the final materials. For information on the status of the copyright claim, contact either the copyright proprietor or the National Science Foundation.

The materials contained herein were developed pursuant to a contract with the National Science Foundation, Grant Number GY-9317. *Contractors undertaking such projects under government sponsorship are encouraged to express freely their professional judgement in the conduct of the project. Points of view or opinions stated do not, therefore, necessarily represent official National Science Foundation position or policy.*

THE POWER TRANSISTOR

An Introduction

THERMAL ENERGY - Its Sources and Transport

Heating occurs when other forms of energy are converted into thermal energy by a particular device or process. For instance, electrical energy is converted into thermal energy by the resistors, wires, and other parts of an electrical circuit. Chemical energy can be converted into heat by the process of burning. Friction converts mechanical energy into heat.

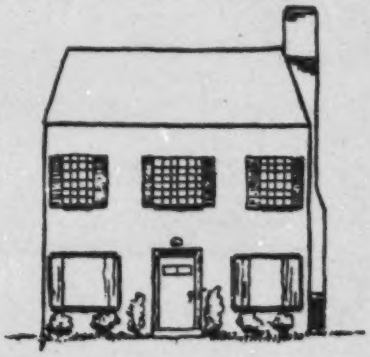
Though there is a great deal of physics in the study of how heat is created, this module is primarily concerned with how heat can be moved from one place to another, thus cooling down or heating up a particular system of interest. This problem arises in many situations, both in industry and in the home. In the case of the transistor used in this module, the problem is simply one of getting rid of heat. The portion of the *input power* that is turned into *heat* by the transistor must be *dissipated* to keep it at a low enough *temperature* to operate properly. In the Parts I and III of this module, you will measure temperature and power, and learn how to control temperature with the help of the physics of heat transfer.

"TRANSIENTS"

Often, something which is at room temperature must be made hotter or colder before it can be used. An example of the case where heating is needed is a soldering iron. Naturally, it does not come up to its final temperature immediately; it takes time for it to warm up. The length of time this takes can be described by a *time constant* which depends on how fast heat is lost by the iron. Since the warming stage lasts for a fairly short time, it is called *transient* behavior. In Part II you will see more examples of transient behavior, as well as how time constants are related to heat flow.

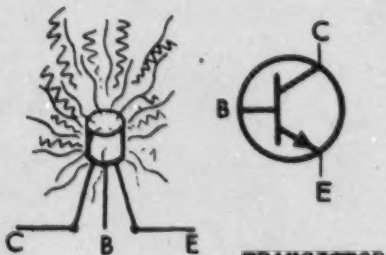
WHERE ARE THE IDEAS USED?

There are a number of situations in which it is either necessary or convenient to have heat transported from one place to another. A knowledge of the physics of heat transfer can be a great help in dealing with these situations. Here are some examples of cases in which heat transfer is important.



Heating and Cooling Buildings: Houses and buildings where people work or live get too hot for comfort in the summer and too cold in the winter. To keep the temperature at a comfortable level, it is necessary to find ways to transport heat from furnaces or electrical heaters to rooms, or from rooms to the outside air. An air conditioner is an example of a room cooling system; it is similar to a refrigerator.

Engines: Internal combustion engines, such as the ones in automobiles and lawn mowers, generate a great amount of heat as the fuel explodes in their cylinders. Some of this heat is used to do useful work. The heat that is left must be taken away by a cooling system of some kind so that the engine won't overheat.



TRANSISTOR

TRANSISTOR SYMBOL

Electronics: Many parts or "components" of an electronic circuit are designed to be used below a certain power level. If this level is exceeded then they get too hot and "burn out" or operate improperly. Various means can be used to get rid of the heat generated by electrical components, thus making it possible to run them at higher power.

WHY EXPERIMENT WITH TRANSISTORS?

A good way to learn about heat transfer is to make measurements of the behavior of a widely used device which can quite easily overheat. A transistor is such a device, and it also has the advantages of being small, and having readily controllable power input. Also, a thorough study of heat dissipation in a power power transistor will illustrate most of the important physics in heat transfer.

MODULE OBJECTIVES

The general goal of this module is to give you an understanding of the principles of heat transfer, and of how these principles apply to practical devices, such as a power transistor.

This involves a knowledge of:

* The measurement of temperature and power;
* The basic quantities used to describe a thermal system (heat capacity, thermal resistance);
* The meaning and description of "transient behavior";
* The basic heat transfer processes (conduction, convection, radiation).

Upon completion of this module you should be able to do the following things to demonstrate your understanding of the module objectives.

When given a power transistor you should be able to:

1. Properly select, install and use a device for measuring its temperature.
2. Determine its power ratings from its specification sheets.
3. Measure the transient response for a power level within its ratings.
4. Measure its final equilibrium temperature for various power levels within its ratings.
5. Find, from a graph of the data, the thermal resistance and time constant of the system.
6. Use the thermal resistance, final temperature, and time constant to find:
    a. the heat capacity of the system
    b. the final temperature of the system for any power input, and
    c. a good operating point for the system;

7. Identify the factors which affect the thermal resistance of the system;

8. Lower the thermal resistance of the system to improve the power dissipation.

You should also be able to explain the meaning of the following terms:

Thermal resistance
Heat capacity and specific heat
Conduction and thermal conductivity
Convection
Radiation

PREREQUISITES:

All you need to understand the material in this module and perform the experiments is a few basic laboratory skills and a knowledge of some algebra and graphing.

POWER, TEMPERATURE, & TRANSISTORS

INTRODUCTION

The terms "temperature" and "power" are used almost constantly in discussions of heat transfer. Since they are such key quantities,most of this section will deal with how they are measured. It will also be important to know how the power transistor operates, and how it is affected by changes in power and temperature. Most of the information is given by the manufacturer on a "specification sheet"; you will observe experimentally an important factor not listed in the specifications as given on page 10.

POWER AND ENERGY. . . .

What is energy? This is not an easy question to answer exactly. In everyday speech, someone who never seems to need a rest from work is said to have a great deal of "energy". Someone who carries heavy boxes up stairs will probably feel quite tired; he has used a large amount of energy doing work. Also, people who can do physical labor faster than others are called stronger or "more powerful" than others.

Our feelings about energy and power can be made more precise in a number of instances. First of all, the amount of work done on a system can often be calculated or measured exactly, and this is equal to the change in energy of that system. The power input to (or dissipated by) the system is defined as the energy going into (or out of) it per unit time. If there is no net heat flow to or from the system, this is the same as the work done on (or by) the system per unit time. Thus, power in *watts* equals energy in *joules* per *second*,that is, 1 watt = 1 joule/second. For example, it takes about 500 joules of energy to carry a 20 pound weight up two flights of stairs no matter how fast it is done. If you could do this in 5 sec., your power would be 500 joules/5 seconds = 100 watts. If you could do it faster, say in 2.5 seconds, your power would go up to 500 joules/2.5 seconds = 200 watts. (Incidentally,746 watts = 1 horsepower, so 200 watts = 0.26 horsepower. Compare this to average ratings for cars and other engines).

P = V x I

Where it comes from:

$$\text{Input Power} = \frac{\text{Energy in}}{\text{time}} = \frac{\text{Work done}}{\text{time}}$$

The voltage is the work needed to take one coulomb of charge across a component:

$$\text{Volts} = \frac{\text{work}}{\text{charge}} \qquad \left[\frac{\text{joules}}{\text{coulomb}}\right]$$

An amp flows if one coulomb of charge passes a given point in one second:

$$\text{Amps} = \frac{\text{charge}}{\text{time}} = \left[\frac{\text{coulombs}}{\text{second}}\right]$$

Therefore:

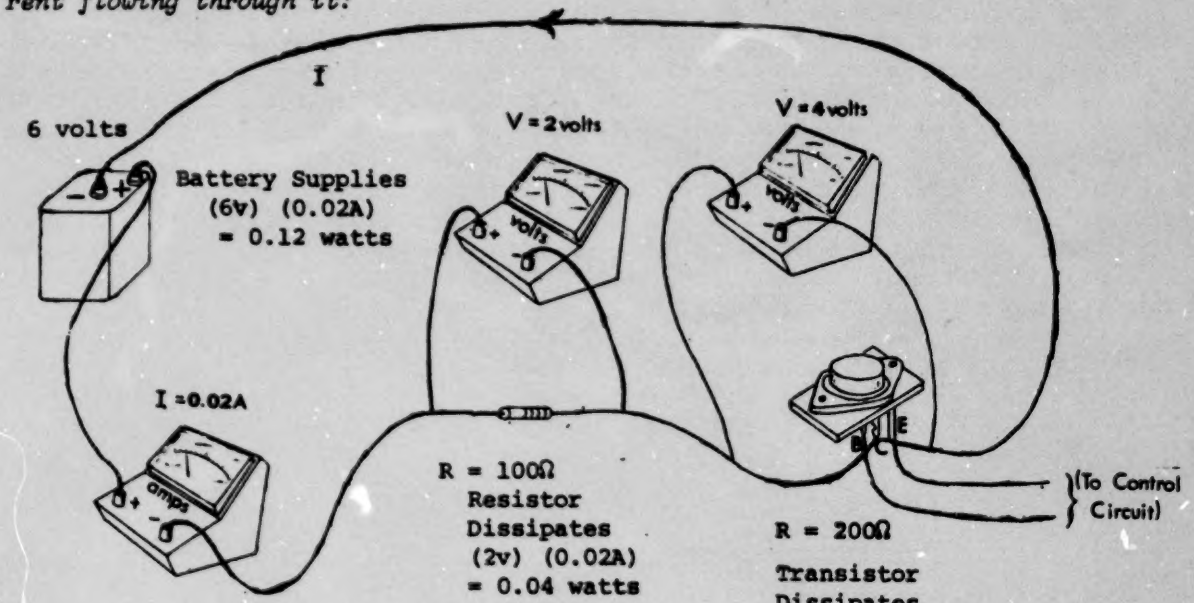
$$\text{Volt x Amps} = \left(\frac{\text{work}}{\text{charge}}\right) \times \left(\frac{\text{charge}}{\text{time}}\right) = \frac{\text{work}}{\text{time}}.$$

$$= \frac{\text{joules}}{\text{second}} = \text{Watts} = \text{power.}$$

In this module, one useful formula for power is the one for electrical power: P = V x I, where V is the voltage drop across a component and I is the current flowing through it. The way that this formula is derived is outlined above. An example using a resistor and a low power transistor is shown at the right. Just why the power input equals the power dissipated in this case, will be explained in later sections.

Other formulas for power will be explained in later sections.

Whatever the circuit element, the electrical power coming into it which must be dissipated is equal to the voltage across the element times the current flowing through it:



Power In = *Power Out*

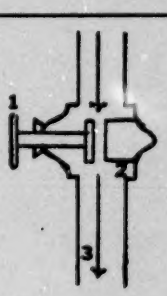
0.12 *watts* = 0.04 *watts* + 0.08 *watts*

CONTROLLING POWER. . . .

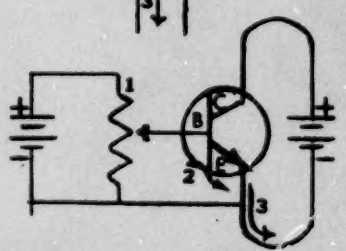
To investigate heat transfer and transients, it will be important to be able to control the power input to the transistor. This could be done either by controlling the voltage or the current. In the experiments of this module, you will basically be controlling current flow, though changes in current will probably cause changes in power supply voltage as well.

The transistor operates somewhat like a water faucet. The potentiometer (the "faucet handle") controls the *base* (B)-*emitter*(E) current (the "valve"). The greater this current is, the greater the *collector*(C)-*emitter*(E) current (the "water flow") will be. In this way the small current in the control circuit controls the large flow of current in the output circuit. This feature of a small current controlling a large one is used for *amplification* - a major use of transistors.

The Faucet Handle (1) controls the valve (2) which controls the water flow (3).



Similarly the potentiometer (1) controls the base-emitter current (2) which controls the collector-emitter current (3).

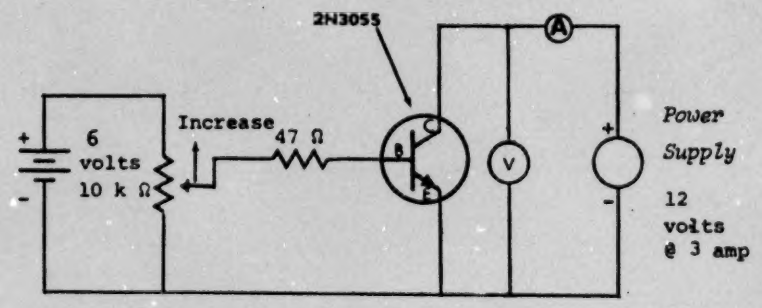


AN INTRODUCTORY EXPERIMENT

INTRODUCTION

The basic electrical circuit for the experiment consists of two parts, a control or "input" section and an "output" section. The control system consists of a 6 volt vattery, a 10 thousand ohms (kΩ) variable resistor (a potentiometer), a 47 ohms (Ω) resistor which protects the circuit from excessive currents, and the base-emitter part of the transistor. The output section consists of a 12 V power supply and the collector-emitter part of the transistor. This part of the circuit would normally be connected to either another transistor or to a speaker or other device. In the experiments of this module, you will simply connect the meters as shown to measure the electrical power input to the transistor.

THE BASIC TRANSISTOR CIRCUIT.



Control Circuit (Input)-Low Current. *Output Circuit - Higher Current.*

A small input current controls a 0 to 3A current flow in the "output" section of the circuit. The 10kΩ potentiometer controls the input current, and the output current is some multiple (typically 100) of the input current. The exact multiplication factor depends on the temperature, as well as on the particular transistor and circuit.

SETTING UP:

* Plug in the transistor leads. Be sure to put the base, collector, and emitter in the correct places. Also, make sure that the base is attached to the transistor with metal screws, because the screws serve as a path for the collector current.
* Connect the meters, power supply and battery. Make sure that the power supply is off, and that everything is attached with the correct polarity.
* Turn the potentiometer fully counter clockwise so that no current will flow in the output circuit when the power supply is turned on.

TESTING THE CIRCUIT:

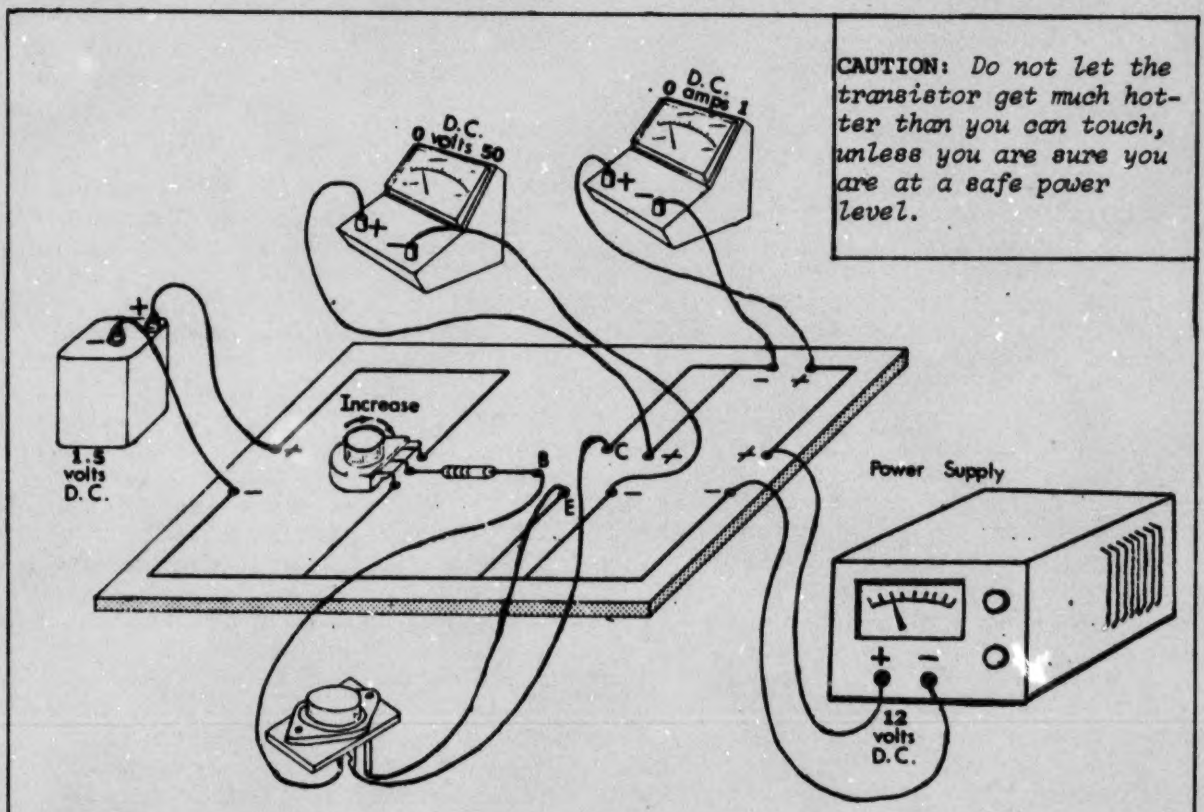
To test the circuit, turn on the power supply and then turn the potentiometer slowly clockwise. At first the current won't increase much, but then it should increase rapidly as the current in the control circuit increases. To make sure the transistor doesn't burn out use your finger as a thermometer. When the transistor gets too hot to touch, turn the current down.

PROCEDURE:

* Let the transistor cool down (a fan speeds this considerably).
* When the transistor feels like it is near room temperature, turn off the fan, if you used one, turn on the power, and set the potentiometer so that 0.1 amp flows in the output circuit.
* Without changing the potentiometer setting, note how the current changes as the transistor heats up.
* When the current reaches 0.75 amp note the voltage and turn off the power immediately. Calculate the power at this 0.75 amp point.

This experiment shows that the transistor's characteristics, such as its amplifying power, depend very strongly on the temperature of the transistor. This is one of the reasons that it is important to know how to control heat flow: in most applications, it is necessary to have constant characteristics, and thus the temperature must be kept constant.

CAUTION: *Do not let the transistor get much hotter than you can touch, unless you are sure you are at a safe power level.*



Your complete electrical circuit should look something like this when completed. The circuit board is convenient but not necessary.

TRANSISTOR....

WHAT WILL IT DO?

The manufacturer's specification sheet for the Power Transistor gives two major types of information. The first kind of information is a brief description of what the transistor does, including its size, use, and "gain". The gain is the factor which tells how much the input current should be multiplied by to give the output current. The value of 20-70 given is for 4 amps and at the usual operating temperature of 25°C or less. As you have seen, this number is very dependent on the temperature of the transistor. Also, the manufacturer usually gives the gain for conditions where the gain is small, so it is not unusual to find a 2N3055 transistor with a gain greater than its rating of 20-70.

HOW MUCH CAN IT TAKE?

Most of the specifications on the sheet are the second type of information, namely, the recommended maximum ratings. Various maximum ratings for voltages, currents, and power are listed and graphed on the sheet. Many of these have already been taken into account in the setup. For instance, note that the maximum collector-emitter voltage is 60 volts, and that your setup uses a 12 volt supply. (The two values of this voltage refer to whether or not the base-emitter is open (0), or is connected with some resistance (R).)

The information you will use in the experiments is given under "Thermal Characteristics" and in the graph called a "Power Temperature Derating Curve". The first of these will be discussed in part two. The second gives the maximum power that the transistor can be dissipating for a given case temperature. Note that as the case temperature goes up, the transistor must have a smaller power input or else it will overheat.

For instance, suppose 8 watts is being put into the transistor as in the experiment on the previous page. The final case temperature at this input power depends on how the transistor is mounted and on whether it has a fan blowing on it. With no special mounting or fan, an experiment would show the case temperature to be about 185°C. Looking at the chart, at 185°C, 8 watts is about the highest power that the transistor can dissipate without overheating. This is why we had you turn off the power when 12V, 0.75 amps was reached.

With a heat sink, an experiment would show the final case temperature at 8 watts to be about 50°C. At this temperature, the curve shows that the transistor could dissipate 95 watts, so 8 watts is certainly a safe input power. Does this mean that with a heat sink, the transistor can be run at 95 watts? No, because as the power is increased, the final temperature increases and as the temperature increases, the maximum power decreases. This somewhat confusing business will be cleared up in part three.

....CHARACTERISTICS

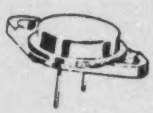
2N3055 POWER TRANSISTOR

NPN SILICON POWER TRANSISTOR

. . . designed for general-purpose, moderate speed, switching and amplifier applications.

- DC Current Gain – h_{FE} = 20-70 @ I_C = 4.0 Adc
- Collector-Emitter Saturation Voltage – $V_{CE(sat)}$ = 1.0 Vdc (Max) @ I_C = 4.0 Adc
- Excellent Safe Operating Area

15 AMPERE
POWER TRANSISTOR
NPN SILICON
60 VOLTS
115 WATTS



*MAXIMUM RATINGS

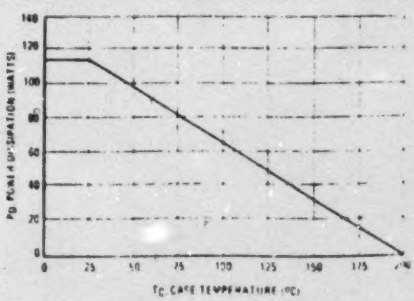
Rating	Symbol	Value	Unit
*Collector-Emitter Voltage	V_{CEO}	60	Vdc
Collector-Emitter Voltage	V_{CER}	70	Vdc
Collector-Base Voltage	V_{CB}	100	Vdc
Emitter-Base Voltage	V_{EB}	7.0	Vdc
Collector Current – Continuous	I_C	15	Adc
Base Current – Continuous	I_B	7.0	Adc
Total Device Dissipation @ T_C = 25°C Derate above 25°C	P_D	115 0.657	Watts W/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}	-65 to +200	°C

THERMAL CHARACTERISTICS

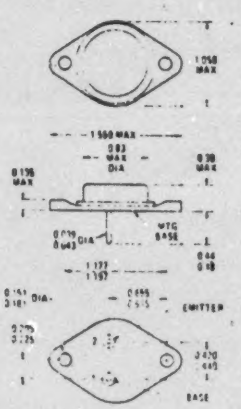
Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction to Case	θ_{JC}	1.52	°C/W

*Indicates JEDEC Registered Data.
**Motorola guarantees this value in addition to JEDEC Registered Data.

FIGURE 1 – POWER TEMPERATURE DERATING CURVE



Safe Area Limits are indicated by Figure 9. Both limits are applicable and must be observed.



CASE 11
(TO-3)

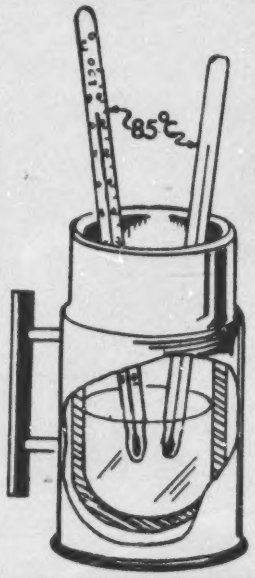
Collector Connected to Case

TEMPERATURE AND THERMOMETERS....

THERMOMETERS. . . .

A device used to measure temperature is called a "thermometer" whether or not it looks like the familiar glass tube variety. Many easily measured properties of matter which depend in a precise way on temperature have been used to make thermometers. Examples of such properties are the volume of a given amount of solid or liquid, and the electrical resistance of certain materials.

The most common variety of thermometers have mercury or colored alcohol in a glass tube. When the temperature goes up the liquid expands, which means that its volume gets larger. This change in volume makes the surface of the liquid move up higher in the tube. By checking what the temperature is with a thermometer already marked in degrees, the height of the liquid in the tube can be associated with a particular temperature. (Making the first thermometer is quite difficult.) Checking a number of heights and temperatures in this way *calibrates* this "liquid in glass" thermometer. Similarly, the value of the resistance of, for instance, a piece of platnium wire can be checked at a number of temperatures, making it into a calibrated thermometer. The thermocouple discussed on the next page generates a voltage which is related to temperature.



The two thermometers are held at the same temperature by well-stirred hot water. The mark on the case of the uncalibrated thermometer is now known to be the 85°C mark. Other water temperatures can be used to similarly mark other points, and thus fully calibrate the new thermometer.

TEMPERATURE SCALES:

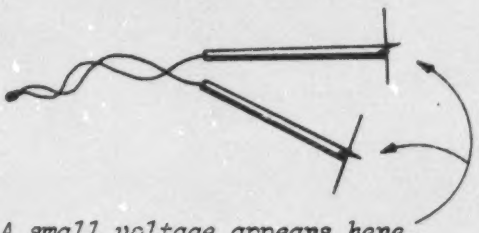
A Brief Summary . . . .

There are a number of temperature scales now in use in the U.S. and elsewhere. The one you are probably most familiar with is the Fahrenheit scale used for household and outdoor thermometers. In this module, the *Celsius* (or Centigrade) scale will be used. If you are unfamiliar with this scale, see the appendix to this section.

THERMOCOUPLES—ANOTHER TYPE OF THERMOMETER

WHAT IS A THERMOCOUPLE?

A thermocouple is a device used to measure temperature, which is based on an interesting fact: when two different metals are placed in contact, a voltage is generated. (In your thermocouple, copper and constantan are used, but other metals are also used.) This voltage depends on temperature, and thus wires made out of different metals can be used to make a thermometer.



A small voltage appears here. This voltage depends on the temperature.

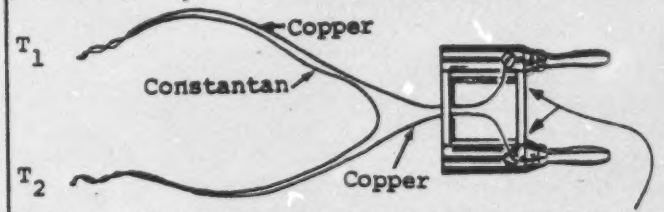
A PROBLEM:

When the two wires shown in the illustration at the left are connected to a voltmeter, a problem arises, since two new junctions (leads to thermocouple wires) are created. These create new voltages which complicate temperature measurement. In particular to create a "reference junction," *both* the thermocouple-meter leads must be kept at the reference temperature, usually 0°C. This is a slightly cumbersome arrangement.

A CONVENIENT ARRANGEMENT:

To get around this problem, yet another junction is introduced, as shown at the right. The trick is to make the meter lead to thermocouple junctions cancel in their effects on the voltage. To do this, both lead-thermocouple junctions should be at the same temperature, and should be between the same kinds of metals. Usually these junctions are both kept at room temperature. The rest of the set-up is shown in the illustration. The way to use the two junctions used for measurement is explained on the next page.

The two junctions are at different temperatures, and thus create different voltages.



When two junctions are used, the "junctions" at the meter leads are of the same kind. The voltages they generate however, are equal and opposite to each other and thus cancel. The only voltages that appear on the meter, therefore are those due to the copper-constantan junctions.

THE REFERENCE JUNCTION

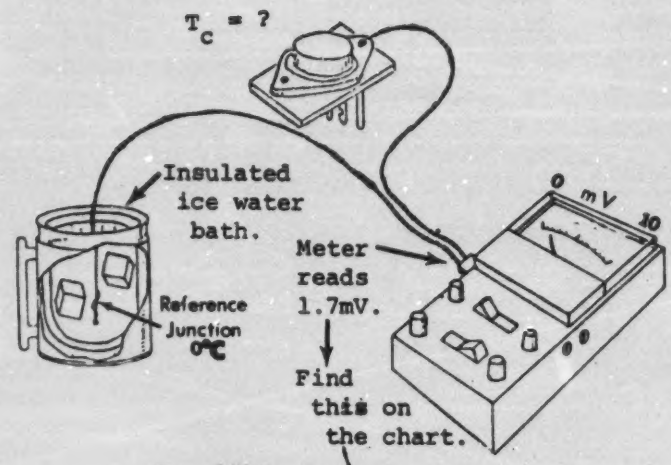
The voltage produced by a thermocouple is nearly proportional to the temperature difference between its two junctions. Because of this, the temperature of one of the junctions must be known accurately in order to use the thermocouple as a thermometer. The most common way of doing this is to keep one junction at the temperature of melting ice, 0°C. Almost all calibration tables assume that the reference junction is at 0°C. To make sure the reference junction really is at the proper temperature, be sure to stir the water frequently, or better yet, put the thermocouple wire in contact with one of the ice cubes. Failure to do this can result in fairly large errors.

USING THE THERMOCOUPLE....

USING THE TABLE:

A small portion of the copper-constantan thermocouple calibration table is shown at the right. The example above it shows how it is used to get the temperature to the nearest degree. With the reference junjunction at 0°C, and the other junction at the temperature to be measured, a voltage reading is taken with a millivoltmeter. In this case the meter reads 1.7 mV. (You probably won't be able to be more accurate than the nearest 0.1 mV.) Going to the chart, the closest value to 1.7 mV is 1.694 mV. To find the temperature, look first at the number in the °C column which is in the same row as the 1.694 value. This number, 40, gives the correct number in the tens' place. To find the ones' place look at the heading of the column above the 1.694, which is a 2. The final result is thus that the transistor temperature to the nearest degree is 42°C.

As another example, suppose the meter read 4.9 mV. The closest value to this on the chart is 4.891 (*not* 4.939) which corresponds to the temperature of 113°C. Of course the table works the other way just as easily. If you want to know what voltage means a temperature of 93°C, just look in the "90 row" and the "3 column" to find 3.952 mV.



T_c = 42°C

1st digit

2nd digit

°C	0	1	2	3	4
(+)0	0.000	0.038	0.077	0.116	0.154
10	0.389	0.429	0.468	0.508	0.547
20	0.787	0.827	0.868	0.908	0.949
30	1.194	1.235	1.277	1.318	1.360
40	1.610	1.652	1.694	1.737	1.779
50	2.035	2.078	2.121	2.164	2.207
60	2.467	2.511	2.555	2.599	2.643
70	2.908	2.953	2.997	3.042	3.087
80	3.357	3.402	3.448	3.493	3.539
90	3.813	3.859	3.906	3.952	3.998
100	4.277	4.324	4.371	4.418	4.465
110	4.749	4.796	4.843	4.891	4.939
	5.227	5.275	5.323		5.420
	5.712	5.761			
	6.204	6.254			

The complete table is shown on page 22.

WHAT TO DO IF YOU DON'T HAVE ANY ICE:

There is an easy way to convert readings made with a reference junction at, say, room temperature to correct temperature readings. You must still know what the temperature of the reference junction is (for instance, from a room thermometer). The trick is to add the voltage corresponding to the reference junction to the meter reading before using the chart to find the actual temperature. Suppose the reference junction is at 20°C. Checking the table, this corresponds to 0.787 mV. If the meter reading is 4 mV, than looking at the chart for the value 4 + 0.787 = 4.787 mV, the temperature of the other junction is 111°C.

THERMOCOUPLE VOLTAGE MEASUREMENTS

CALIBRATING THE METER

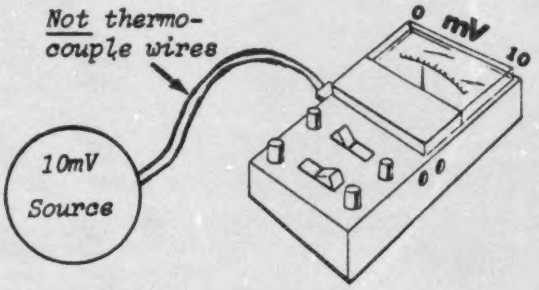
Thermocouples have been calibrated for various metals in millivolts versus temperature, and the results are recorded in tables. To make use of the tables, however, it is necessary to have a meter calibrated in millivolts. Assuming that you have an uncalibrated amplifier/meter system, there are two easy ways to calibrate it:

METHOD 1: By far the simplest way is to use a known 10mV source:

* Short the input leads to the meter, and adjust the zero setting.
* Attach the leads to the 10mV source and adjust the "gain" control until the meter reads full scale.

The meter is now calibrated and ready for use with the thermocouple.

First zero the meter with the leads touching.....

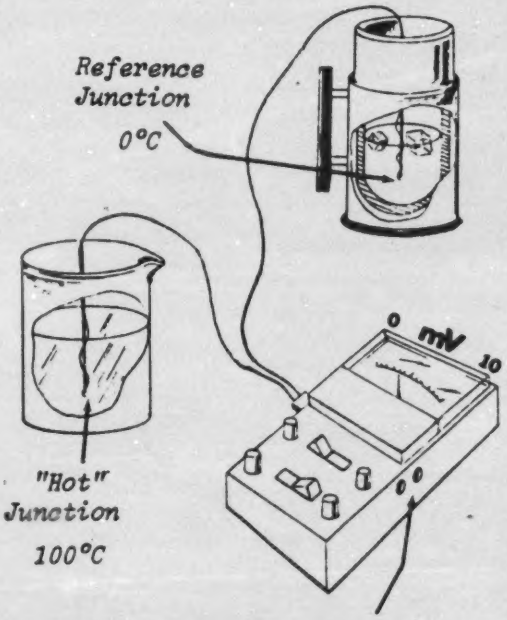


.....then attach the meter to a 10mV source, and set the gain to make it read full scale.

METHOD 2: Another calibration technique is to use the thermocouple as a source of a known voltage. For instance, if one junction is in an ice water bath and the other is in boiling water, then the difference in temperature between the junctions is 100°C. Refering to the table on the previous page (or the more complete one on page 19), this temperature difference creates a voltage of about 4.3mV (actually 4.277mV, but neither the meter or this particular thermocouple setup is that accurate). Knowing this, the procedure is as follows:

* Short the thermocouple leads and adjust the zero setting.
* Put one of the leads in ice water and the other in boiling water, and adjust the gain so that the meter reads 4.3mV.
* If the meter goes the wrong way, reverse the connections of the leads to the meter, and start again.

First zero the meter with the thermocouple leads touching...



...then, with the temperature difference equal to 100°C, set the meter at 4.3.

MEASURING TEMPERATURE....

FINDING TEMPERATURES TWO WAYS. . . .

The usual way we measure temperature in the home or outside is with a mercury in glass or alcohol in glass thermometer. In the experiments on this page, you will compare the performance of a mercury in glass thermometer to that of a thermocouple.

MEASURING ROOM TEMPERATURE

As a first step, use the calibrated meter to find the room temperature voltage for the thermocouple when it has a 0°C reference junction temperature. Look up this value in the table and compare the temperature you find to the room temperature reading of a mercury thermometer. Record these two temperatures on the chart at the right.

Room Temperature:

T_{merc} = _____

$T_{t'cple}$ = _____

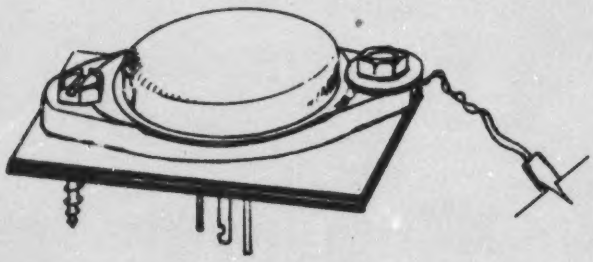
Response Time:

t_{merc} = _____

$t_{t'cple}$ = _____

RESPONSE TIMES

Next take the reference junction out of the ice water bath and dry it off. The voltage should be 0 when both junctions are at room temperature. When the voltage is 0, put the reference junction back in the ice water and measure the time it takes for voltage to come back to the room temperature value. This time is quite brief so you may want to just count the seconds ("One thousand 1, one thousand 2..."). Do the same experiment with the mercury thermometer: put it in the water and see how long it takes for it to read nearly 0°C. Record these two "response times" on the chart.



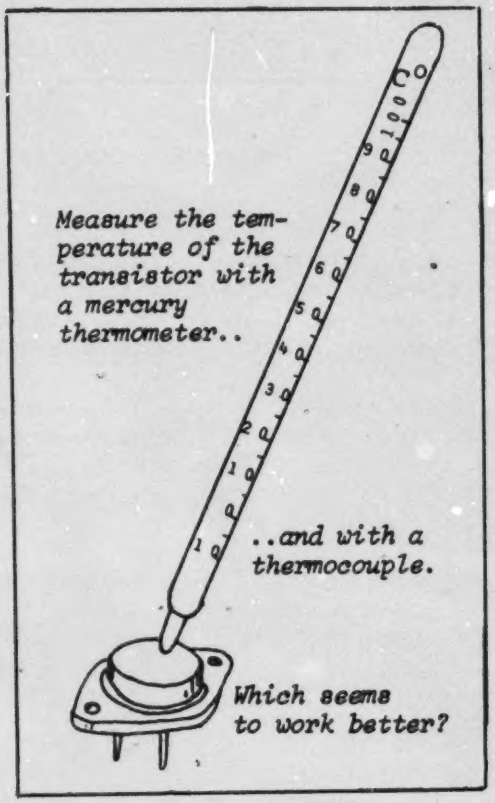
ATTACHING THE THERMOCOUPLE TO THE TRANSISTOR

For the next experiment, the thermocouple should be attached firmly to the transistor. To do this, put the thermocouple under a washer on the mounting screw, and tighten the screw so that it is moderately tight.

TRANSISTORS, TEMPERATURE, AND RESPONSE TIMES

Now turn the transistor input power to 4 watts (how many amps?). Watch the thermocouple voltage change. Be sure to keep correcting the power to keep the input down to 4 watts. The transistor may get too hot to touch. (At what temperature does this happen?). Finally (in about 10 to 15 minutes) the temperature will level off at some value. Find out what this temperature is and record it in the chart below.

Next, try to find the temperature with a mercury thermometer. Still keeping the input power at 4 watts (it has a tendency to drift) try various ways of holding the thermometer to the transistor. How long does it take for it to come up to its final temperature? Does it give the same reading as the thermocouple? If not, which one do you think is correct? What method of contact seems to give the best results? Which thermometer would you prefer to work with in terms of convenience of monitoring temperature over a period of time?


Measure the temperature of the transistor with a mercury thermometer..
..and with a thermocouple.
Which seems to work better?

Transistor Temperature:

T_{merc} = _____

$T_{t'cple}$ = _____

Response Time On Transistor:

t_{merc} = _____

CHOOSING A THERMOMETER...

WHICH ONE IS BEST?

In the next few pages, four types of thermometers will be discussed. There are a number of important differences between them, and thus one thermometer may be useful where another isn't. What kinds of things is it important to look for? In general a good thermometer should:

1. Make *good thermal contact* with the object being measured.
2. Be small enough, so that it *won't change the temperature.*
3. *Respond reasonably quickly* to change in temperature.
4. Have *adequate sensitivity:* That is, there should be an observable change in the indication with a small temperature change.
5. *Respond over the range of interest,* and not be damaged by the highest and lowest temperatures in the experiment.
6. Be *calibrated:* that is, it should have a *scale* and *accurately* indicates the temperature. If it does not directly indicate temperature, then there must be a simple way of converting the reading to temperature.

"RESPONSE TIMES" AND ACCURACIES COMPARED:

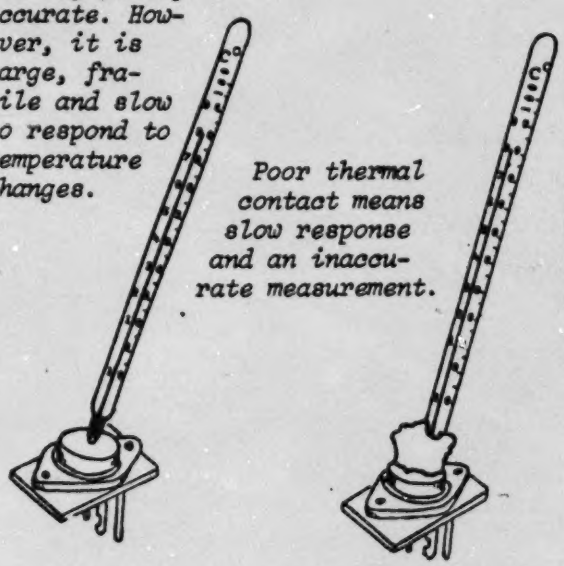
The time that it takes for a thermometer to read the temperature of an object when it starts at another temperature (the *response time*) depends mainly on two things. The first is how well heat can be transferred to the thermometer from the object. The second is how much heat it takes to raise the temperature of the thermometer by a specific amount. In the case of the mercury thermometer, the poor thermal contact to the transistor and the unwanted insulation provided by the glass case make it hard for heat to flow into the mercury. Also, since there is quite a bit of mercury to be heated, it takes a relatively large amount of heat to raise its temperature by one degree. These two factors make the mercury thermometer respond slowly. Even when it does reach its final temperature, it may be giving a low reading, since there is a temperature drop (similarly to a voltage drop in an electrical circuit) across the "thermal resistance" between the case and the thermometer. Thermal resistance is an important and concept which will be discussed in detail in parts II and III.

....FOR YOUR EXPERIMENT

MERCURY THERMOMETERS WORK POORLY. .

The mercury in glass thermometer is calibrated on the case, and is usually fairly accurate. However, it is large, fragile and slow to respond to temperature changes.

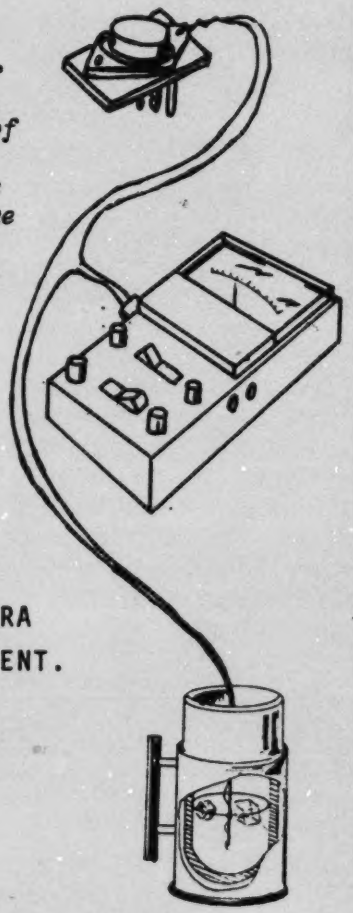
Poor thermal contact means slow response and an inaccurate measurement.



The thermocouple doesn't affect the measurement because its mass is small. It can make good thermal contact with the transistor, and responds fairly quickly and accurately to temperature changes.

. . THERMOCOUPLES ARE BETTER. . .

Even with better thermal contact, the large mass of mercury and the glass walls make the response time slower, and the reading less accurate than desired.



. . BUT NEED EXTRA EQUIPMENT.

The thermocouple on the other hand, makes excellent thermal contact with the transistor when it is soldered or screwed to the transistor case. It also has a small mass, so it responds quickly to temperature changes, and doesn't change the temperature of the transistor.

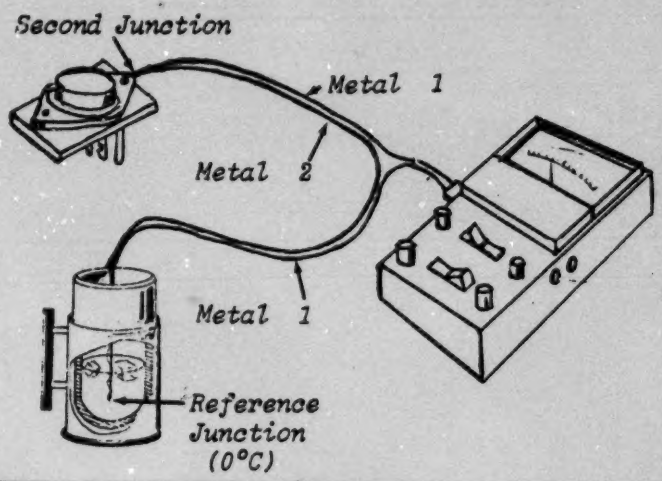
We have chosen the thermocouple for these experiments since it meets our requirements quite well and is relatively inexpensive and convenient to use. The *thermistor* and *resistance thermometer* described on the next two pages will work nearly as well, however.

COMPARING THREE

What Is It? The Setup

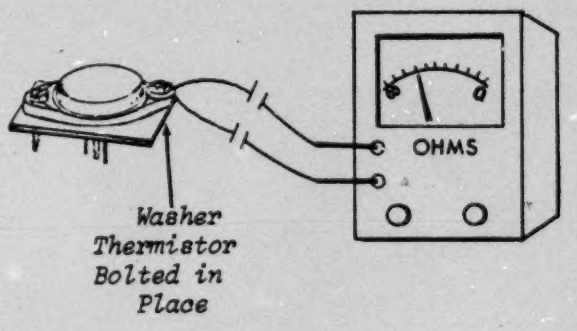
THE THERMOCOUPLE. . .

. . . is made of two types of metal wire, as shown at the right. It produces a voltage difference between its two junctions when the junctions are at different temperatures. The greater the difference in temperature, the greater the voltage produced. The value of the voltage depends only on the types of metal involved, and on the temperature difference, and not on the length or thickness of the wires.



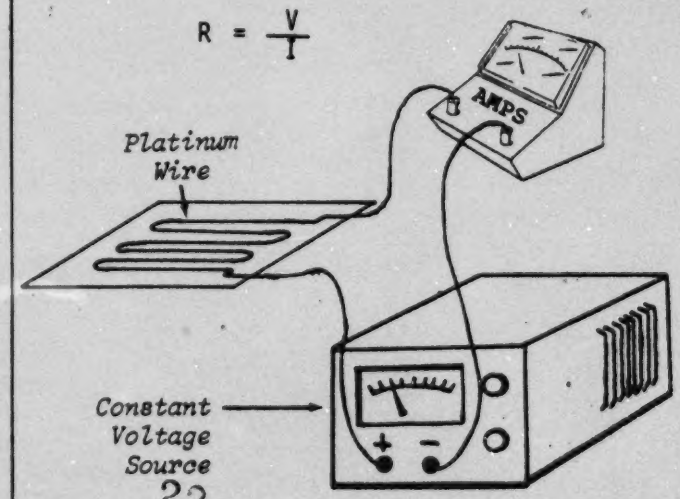
THE THERMISTOR. . .

. . . is a kind of resistor, Its resistance decreases as the temperature increases. The material it is made of is a type of "semiconductor." This same sort of material is used to make transistors and diodes. There are many shapes and sizes of thermistors, and their resistance depends on the size as well as the type of material used to make them. The one at the right is a "washer" type, held down by a screw.



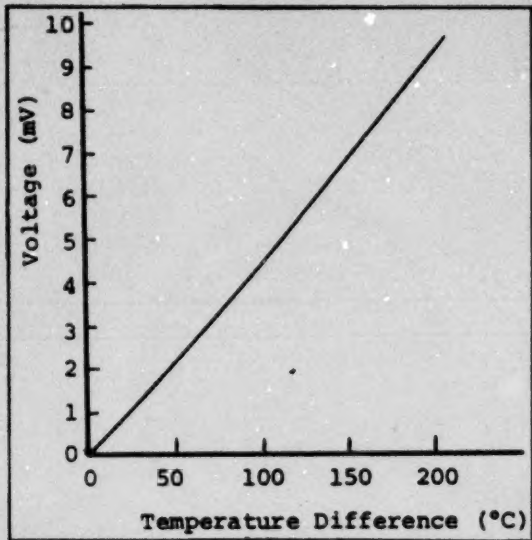
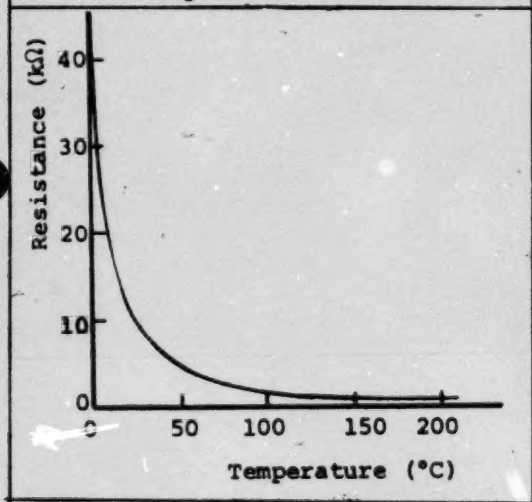
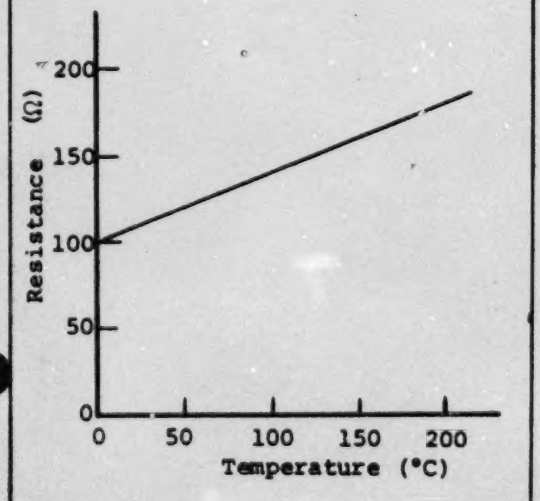
THE RESISTANCE THERMOMETER. . .

. . . is similar to a thermistor, except that its resistance increases as the temperature increases. Instead of being made of a semiconductor material it is usually a metal such as platinum or nickel. The one at the right is a simple variety; for more exact work, the wire is especially mounted and enclosed in an air-tight case. Other kinds of mountings are also used, but the operating principles are the same in all cases.



22

THERMOMETERS

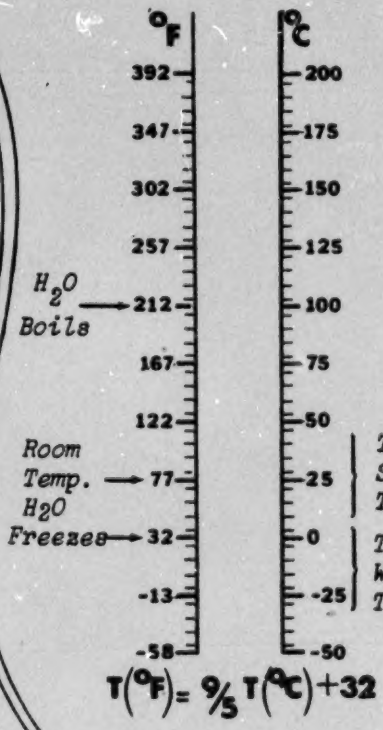
Calibration	Characteristics	Comments
	*Range:* -260°C to +900°C *Response Time:* About 2 Seconds *Accuracy:* ±0.2°C	The numbers given at the left are for a copper-constantan thermocouple. Other thermocouples can be used to as high as 1700°C, but they are seldom used for temperatures lower than this one can go. Thermocouples respond faster than most types of commercially available thermometers. Their major disadvantages are that they require a quite sensitive voltmeter, and they aren't accurate enough (even with better setups) for high precision work. A major advantage of a thermocouple is that its voltage-temperature relation is very stable, that is, it doesn't change with time as does the resistance -temperature relation of many thermistors.
	*Range:* -60°C to +300°C *Response Time:* Several Seconds *Accuracy:* ±? (Less at High T)	The numbers given are for a typical commercially made thermistor. Various types of thermistor can be used for measuring temperatures near absolute zero (-273°C), and they can be made to have response times of about 10^{-3}sec. A major difficulty with thermistors is that unless they are properly aged befor use, they must be calibrated frequently for accurate results. In spite of this and their typically slow response times, their ease of use and high sensitivity (large change in resistance for a small change in temperature) make them widely used.
	*Range:* -250°C to +800°C *Response Time:* About 1 Second *Accuracy:* ±0.2°C	When care is taken to mount a platinum wire properly, it is accurate enough to be used as a temperature standard. Resistance thermometers with this accuracy are, however, quite expensive, and they also require a "resistance bridge" to make accurate measurements of the resistance. In any type of mounting, the resistance-temperature relation of this thermometer is linear to within better than 0.2% over the range of temperatures used in this module (0° to 200°C), and is nearly as linear outside this range. This makes it very easy to accurately convert resistance readings to temperature. The platinum resistance thermometer described at the left is one of the least accurate types of resistance thermometers.

TEMPERATURE SCALES

TEMPERATURE SCALES:

A Brief Summary. . . .

The Celsius scale (the same as Centigrade scale) of temperature is the one that will be used throughout this module. It is related into the system commonly used in America, the Fahrenheit scale, as shown in the diagram at the right. Another scale often used for scientific work is the Kelvin scale. This scale has the same size units as the Celsius scale, but starts at a different place, thus: $T(°K) = T(°C) + 273$. The Kelvin scale is called an "absolute" scale because 0°K is believed to be the lowest attainable temperature.



Many scales of temperature are in common use. The table at the left compares the Fahrenheit scale found on most American household thermometers to the Celsius scale used in this module. Besides being a scale often used by scientists the Celsius scale is very commonly used in most countries beside the U.S.A.

CALIBRATION TABLE

Copper vs. Constantan Thermocouple — Reference Junction 0°C

°C	0	1	2	3	4	5	6	7	8	9
					millivolts					
−190	−5.379	−5.395	−5.411	—	—	—	—	—	—	—
−180	−5.205	−5.223	−5.241	−5.258	−5.276	−5.294	−5.311	−5.328	−5.345	−5.362
−170	−5.018	−5.037	−5.056	−5.075	−5.094	−5.113	−5.132	−5.150	−5.169	−5.187
−160	−4.817	−4.838	−4.858	−4.878	−4.899	−4.919	−4.939	−4.959	−4.978	−4.998
−150	−4.603	−4.625	−4.647	−4.669	−4.690	−4.712	−4.733	−4.754	−4.775	−4.796
−140	−4.377	−4.400	−4.423	−4.446	−4.469	−4.492	−4.514	−4.537	−4.559	−4.581
−130	−4.138	−4.162	−4.187	−4.211	−4.235	−4.259	−4.283	−4.307	−4.330	−4.354
−120	−3.887	−3.912	−3.938	−3.964	−3.989	−4.014	−4.039	−4.064	−4.089	−4.114
−110	−3.624	−3.651	−3.678	−3.704	−3.730	−3.757	−3.783	−3.809	−3.835	−3.861
−100	−3.349	−3.377	−3.405	−3.432	−3.460	−3.488	−3.515	−3.542	−3.570	−3.597
−90	−3.062	−3.091	−3.120	−3.149	−3.178	−3.207	−3.235	−3.264	−3.292	−3.320
−80	−2.764	−2.794	−2.824	−2.854	−2.884	−2.914	−2.944	−2.974	−3.003	−3.033
−70	−2.455	−2.486	−2.518	−2.549	−2.580	−2.611	−2.642	−2.672	−2.703	−2.733
−60	−2.135	−2.167	−2.200	−2.232	−2.264	−2.296	−2.328	−2.360	−2.392	−2.423
−50	−1.804	−1.838	−1.871	−1.905	−1.938	−1.971	−2.004	−2.037	−2.070	−2.103
−40	−1.463	−1.498	−1.532	−1.567	−1.601	−1.635	−1.669	−1.703	−1.737	−1.771
−30	−1.112	−1.148	−1.183	−1.218	−1.254	−1.289	−1.324	−1.359	−1.394	−1.429
−20	−0.751	−0.788	−0.824	−0.860	−0.897	−0.933	−0.969	−1.005	−1.041	−1.076
−10	−0.380	−0.417	−0.455	−0.492	−0.530	−0.567	−0.604	−0.641	−0.678	−0.714
(−)0	−0.000	−0.038	−0.077	−0.115	−0.153	−0.191	−0.229	−0.267	−0.305	−0.343
(+)0	0.000	0.038	0.077	0.115	0.154	0.193	0.232	0.271	0.311	0.350
10	0.389	0.429	0.468	0.508	0.547	0.587	0.627	0.667	0.707	0.747
20	0.787	0.827	0.868	0.908	0.949	0.990	1.030	1.071	1.112	1.153
30	1.194	1.235	1.277	1.318	1.360	1.401	1.443	1.485	1.526	1.568
40	1.610	1.652	1.694	1.737	1.779	1.821	1.864	1.907	1.949	1.992
50	2.035	2.078	2.121	2.164	2.207	2.250	2.293	2.336	2.380	2.423
60	2.467	2.511	2.555	2.599	2.643	2.687	2.731	2.775	2.820	2.864
70	2.908	2.953	2.997	3.042	3.087	3.132	3.177	3.222	3.267	3.312
80	3.357	3.402	3.448	3.493	3.539	3.584	3.630	3.676	3.722	3.767
90	3.813	3.859	3.906	3.952	3.998	4.044	4.091	4.138	4.184	4.230
100	4.277	4.324	4.371	4.418	4.465	4.512	4.559	4.606	4.654	4.701
110	4.749	4.796	4.843	4.891	4.939	4.987	5.035	5.083	5.131	5.179
120	5.227	5.275	5.323	5.372	5.420	5.469	5.518	5.566	5.615	5.663
130	5.712	5.761	5.810	5.859	5.908	5.957	6.007	6.056	6.105	6.155
140	6.204	6.254	6.303	6.353	6.403	6.453	6.503	6.553	6.603	6.653
150	6.703	6.753	6.803	6.853	6.904	6.954	7.004	7.055	7.106	7.157
160	7.208	7.258	7.309	7.360	7.411	7.462	7.513	7.565	7.616	7.667
170	7.719	7.770	7.822	7.874	7.926	7.978	8.029	8.080	8.132	8.184
180	8.236	8.288	8.340	8.392	8.445	8.497	8.549	8.601	8.654	8.707
190	8.759	8.812	8.864	8.917	8.970	9.023	9.076	9.129	9.182	9.235
200	9.288	9.341	9.394	9.448	9.501	9.555	9.608	9.662	9.715	9.769
210	9.823	9.877	9.931	9.985	10.039	10.093	10.147	10.201	10.255	10.309
220	10.363	10.417	10.471	10.526	10.580	10.635	10.689	10.744	10.799	10.854
230	10.909	10.963	11.018	11.073	11.128	11.183	11.238	11.293	11.348	11.403
240	11.459	11.514	11.569	11.624	11.680	11.735	11.791	11.847	11.903	11.959
250	12.015	12.071	12.126	12.182	12.238	12.294	12.350	12.406	12.462	12.518
260	12.575	12.631	12.688	12.744	12.800	12.857	12.913	12.970	13.027	13.083
270	13.140	13.197	13.254	13.311	13.368	13.425	13.482	13.539	13.596	13.653
280	13.710	13.768	13.825	13.882	13.939	13.997	14.055	14.112	14.170	14.227
290	14.285	14.343	14.400	14.458	14.515	14.573	14.631	14.689	14.747	14.805
300	14.864	14.922	14.980	15.038	15.096	15.155	15.213	15.271	15.330	15.388
310	15.447	15.506	15.564	15.623	15.681	15.740	15.799	15.858	15.917	15.976
320	16.035	16.094	16.153	16.212	16.271	16.330	16.389	16.449	16.508	16.567
330	16.626	16.685	16.745	16.804	16.864	16.924	16.983	17.043	17.102	17.162
340	17.222	17.281	17.341	17.401	17.461	17.521	17.581	17.641	17.701	17.761
350	17.821	17.881	17.941	18.002	18.062	18.123	18.183	18.243	18.304	18.364
360	18.425	18.485	18.546	18.607	18.667	18.727	18.788	18.849	18.910	18.971
370	19.032	19.093	19.154	19.215	19.276	19.337	19.398	19.459	19.520	19.581
380	19.642	19.704	19.765	19.827	19.888	19.949	20.011	20.072	20.134	20.195
390	20.257	20.318	20.380	20.442	20.504	20.565	20.627	20.688	20.750	20.812

Review

SUMMARY

Heating occurs when chemical, mechanical, electrical, or some other form of *energy* is converted into *thermal energy* by some device or process.

Temperature is a precise measure of "hotness" or "coldness" and can be measured by many different devices generally called *thermometers*. Liquid in glass thermometers, resistance thermometers, thermistors, and thermocouples are examples of such devices.

The *thermocouple* creates a voltage which depends on the temperature between two *junctions* of unlike metals. This voltage is converted to temperature readings by the use of *calibration tables*.

Power (in *watts*) is *energy* (in *joules*) per unit time (in *seconds*); the *electrical* power going into a component of a circuit with a steady current in it is simply

$$P = VI$$

where V is the voltage across the component, and I is the current flowing through it.

To keep power transistors, engines, and other systems at a low enough *temperature* to operate properly, the portion of the *input power* which is turned into *heat* must be *dissipated*.

The first experiment of this section showed that the power transistor's *characteristics*, such as its *gain*, depend strongly on the temperature. To keep the characteristics constant, the temperature must be controlled.

The second experiment of this part showed that thermocouples *respond more quickly* to temperature changes than a common mercury in glass thermometer. Also the thermocouple *disturbed the measurement less*, and was more *accurate* than the mercury thermometer because of its *small size* and *good thermal contact* with the transistor.

QUESTIONS

1. Describe how you could calibrate a thermistor. What would you need and what would you do?

2. Could the thermocouple you used in the experiments be used to accurately measure a change in temperature that took place in 0.1 sec.? in 2 sec.? in 15 sec.? Why or why not?

3. Is a mercury thermometer more accurate for measuring changes in water temperature or changes in air temperature? Explain. Would the same be true of thermocouples?

4. What is the difference between sensitivity and accuracy? Which is more important in measuring small changes in temperature?

PROBLEMS

1. If a resistor can take 1/2 watt before burning out, what voltage can be dropped across it if it must be able to carry 1 mA in a particular application? What is the value of the resistor if 1 mA flowing in the circuit implied that the maximum power was being input to the resistor? (Recall Ohm's law.)

2. Using the power derating curve, determine the maximum power the 2N3055 transistor can take at the following case temperatures: 25°C, 120°C, 200°C. What is the greatest safe case temperature for input power of 12 watts? 40 watts? 115 watts?

3. Again using the derating curve, find the maximum current that can flow in the transistor if the case temperature is kept at 45°C, and the collector-emitter voltage is kept at 40 V.

4. The table below expresses a convenient way to describe thermocouples, by their *thermoelectric power*. If a thermocouple has a thermoelectric power of .05 mV/°C, and the temperature difference between its junctions is 70°C, then the measured voltage will be

Thermocouple Pair[1]	Color Code[2]	Thermoelectric Power (α) mV/°C (for 0-100°C)	Useful Temperature Range (°C)
COPPER - constantan	BLUE - red	0.0424	-200 to +300
IRON - constantan	WHITE - red	0.0528	-200 to +1300
CHROMEL - constantan	PURPLE - red	0.063	0 to +1100
CHROMEL - alumel	YELLOW - red	0.041	-200 to +1200

[1]The polarity of the capitalized material is positive with respect to the material in lower case type when the measuring junction exceeds the temperature of the reference junction.

[2]Standard wire insulation color code for thermocouples.

$$(.05\ \text{mV/°C}) \times (70\text{°C}) = 3.5\ \text{mV}.$$

More generally, calling the thermoelectric power α, the voltage V, and the junction temperature difference ΔT,

$$V = \alpha(\Delta T).$$

Use the table and this formula to answer the questions below.

a) Using the color code, check which type of thermocouple you used in you experiments.
b) With a 0°C reference junction, what voltage would be produced by an iron-constantan thermocouple with its measuring junction attached to a power transistor at 100°C?
c) If a chromel-alumel thermocouple produced a voltage of 4 mV, what would the difference in temperature between its junctions?

5. A 2N3055 transistor has a chromel-constantan thermocouple attached to it. The thermocouple has a reference junction at 20°C (room temperature), and the voltage between the junctions is 2.5 mV. What is the transistor temperature? What is the maximum power that could safely be going into the transistor?

TRANSIENTS

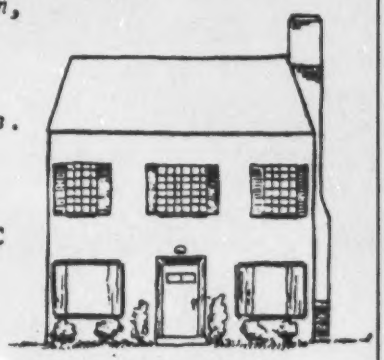
INTRODUCTION

The word "transient" means "temporary", or "quickly passing". In everyday speech, a guest at an inn who is only staying for a short time is called a "transient guest" as opposed to a "permanent resident". In physics, a change that takes place between two long lasting *equilibrium* or *steady states* is called a *transient change*. The time it takes for these transient changes to take place is often described by a *time constant*.

AN EXAMPLE OF EQUILIBRIUM STATES AND TRANSIENTS. . .

As a simple example of these ideas, consider what happens when a room is heated in the winter. Before the heating system is turned on, the room is cold. It is in an equilibrium state at the temperature of the outside air. Since this is an equilibrium situation, the temperature won't change unless some new influence affects the air in the room. When the heater is turned on, the room temperature goes up. This is a period of *transient* temperature *rise* before a new equilibrium state at a higher temperature than the outside air is reached. This new equilibrium is not one in which nothing is happening: the heat that is being lost through the walls and windows is being replaced from the heater, so that the net effect is to keep the temperature unchanged.

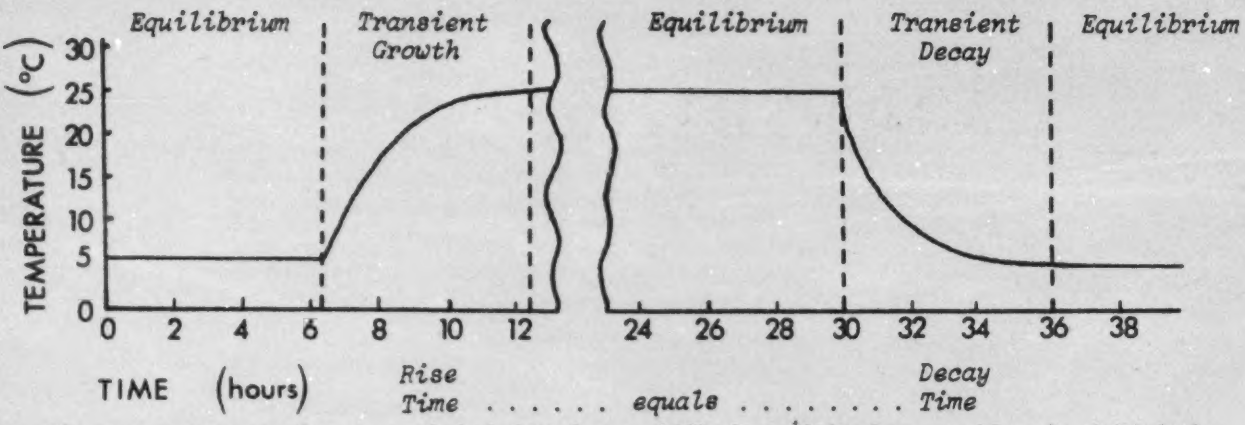
When a heater is turned on or off in a room, the temperaturn undergoes transient changes.



The graph on the next page shows how temperature varies with time for the case described in the text.

Suppose that the situation is changed again by turning off the heater a few hours later. Then, assuming that the outside temperature remains the same, the room temperature would go down in a *transient decay* to the original outside air temperature. The time it takes the room to cool down is very nearly the same as the time it takes for it to heat up, if the state of the room (including whether the windows are open, etc.) hasn't changed. Just how the heating and cooling times are related to the time constant will be described later.

The temperature of the room for this example is plotted against time in the graph. Of course, this is a greatly simplified situation (outside temperature constant, and a heater with no thermostat) so the graph isn't what you would measure if you tried the experiment in the graph on the next page.



The temperature of a room initially in equilibrium with the outside air (which is assumed to be constant at 5°C) undergoes various stages of transient and equilibrium behavior as a heater is turned on and off.

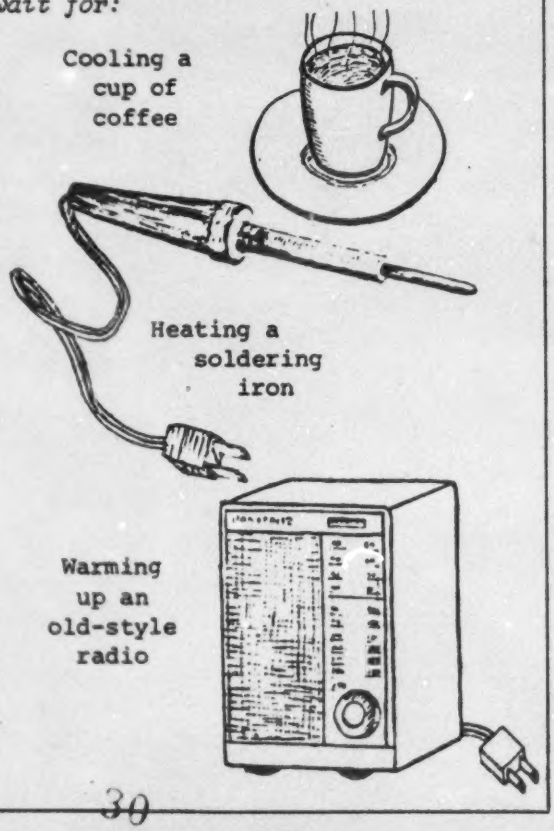
TRANSIENTS OCCUR IN A NUMBER OF SITUATIONS. . . . .

Thermal Transients:

A number of the things we use each day must be hotter or colder than room temperature to be useful. Some examples are an automobile engine, a pressure cooker, a refrigerator, and the tubes of an older style radio or T.V. We sometimes have to wait a few minutes for things such as these to warm up or cool down; this warming or cooling time is a period of transient temperature change.

In all of the cases listed above, the fact that systems do not change immediately from one equilibrium state to another is at most a minor problem. In Part I you saw an example of where transients can be a major difficulty - in measuring temperatures. A mercury thermometer initially at room temperature goes through a transient stage when placed in ice water. Finally it comes to a new equilibrium at 0°C, but it takes a while for it to do so. Because of its long response time, it it inaccurate for measurements where fast temperature changes take place. When you measure the transient change in the transistor case temperature in the experiments of this section, you will need a thermometer that responds quickly, that is, has fairly fast response time. The thermocouple has this property.

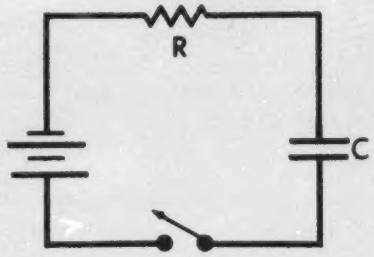
Some thermal transients we have to wait for:



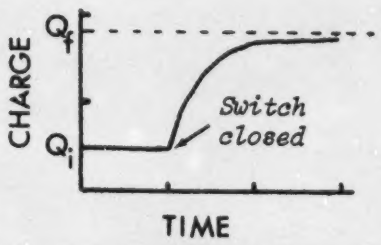
Electrical Transients:

Other transients occur in electrical circuits besides the heating of the components. The simplest circuit in which this is true is shown at the right. Here, a capacitor starts out uncharged, $Q_i = 0$, (first equilibrium state). When the switch is closed, it charges up (transient growth) until it reaches a final charged state, Q_f, (final equilibrium state). The time of charging depends only on the values of the resistance, R, and the capacitance, C, and not on the voltage applied. The time for the capacitor to become 95% fully charged is equal to about 3 RC. A direct analogy can be made between this circuit and a "thermal circuit" with a *Thermal resistance*, R, and a *heat capacity*, C, as you will see later in the module.

The charge on the capacitor shows the same type of transient behavior as the temperature of a heating room.



The time to charge is about equal to 3RC.

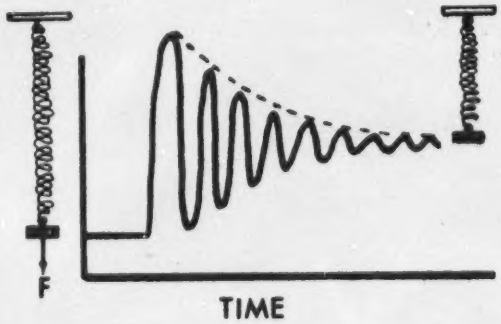


Oscillating Transients:

Not all transients behave like those important in heat flow. Some systems oscillate back and forth for a while before coming to a new equilibrium state. The mass on a spring at the right shows an example of this. In its first equilibrium state it is held down at a certain height above the floor. When it is let go, goes up and down for a while before it settles down at a new height, as shown in the graph. In this case it is the *amplitude* of the oscillations that undergoes transient change. Initially the amplitude is large but it continually decreases as the spring oscillates around its new equilibrium position. The characteristic curve of transient change is seen by connecting the peaks of the oscillations.

This kind of "oscillating transient" is important in a number of cases, but since it does not occur in most temperature changes, it will not be discussed further in this module.

Another type of transient is shown by the height of a mass on a spring.



Mass held down by a force, F.

When released, the mass comes finally to rest at a new height, after bobbing up and down.

A SIMPLE EXPERIMENT...

...TRANSIENTS IN A MERCURY THERMOMETER

The heating and cooling of the mercury thermometer demonstates most of the principles of transients quite well. The object of these experiments is to look at thermometer transients in detail. (Note: In this experiment, as well as in the one on thermistors, there are a number of things to be done in a short period of time. Because of this, you will probably find it helpful to work with another person.)

PREPARATION:

Before preforming the experiment, prepare two data tables like the one shown. The entries in the time column should be about every 3 seconds and extend to times greater then the response time of your thermometer as determined in Part I.

t (sec.)	T(°C)
0	
3	
6	
9	
⋮	

Next, fill a beaker with hot tap water (the particular temperature isn't important).

Also fill the insulated container used for the thermocouple reference junction with ice water. This will provide a convenient temperature bath.

PROCEDURE:

1. PUT THE MERCURY THERMOMETER in the hot water bath, and wait until it comes up to temperature.

   When the temperature has become constant, record it as the t = 0 sec. temperature.

2. TRANSFER THE THERMOMETER quickly to the cold water, so that its temperature doesn't go down very much before it gets there.

3. START COUNTING seconds immediately. Take data every three seconds until the temperature has stopped changing. The person who is counting can call out readings to the other person who records them in the table. If you do this by yourself, you may have to remember the numbers, record them, and do it again to check yourself.

4. REVERSE THE EXPERIMENT by putting the thermometer back in the warm bath, and recording the numbers for transient growth in the second data table.

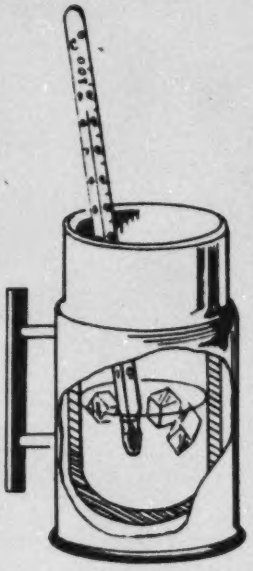
OPTIONAL: Try the above experiment using different values for the hot and cold water baths.

Start with the mercury thermometer in warm water.....

WARM WATER

.....quickly transfer it to ice water so that its initial temperature is that of the warm water.....

ICE WATER

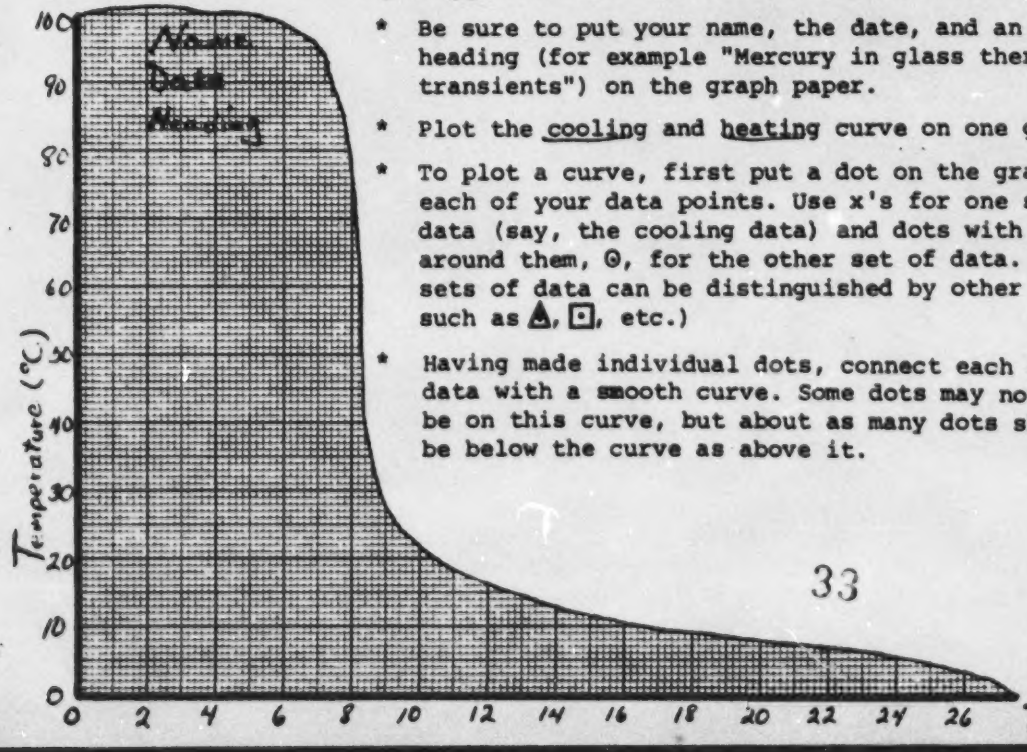


.....and then take readings every three seconds, counting out the seconds as well as you can. While the warm water is still at about the same temperature, try the reverse (cold to hot) process. Also try another warm water temperature.

NOTE: Have one person count seconds and take readings, as the other records these readings in a data table.

GRAPHING THE DATA . . .

When you are done taking data, graph them on a graph similar to that shown below. If you are short on time, do this later. In plotting the data, the following suggestions should be helpful:



- Be sure to put your name, the date, and an adequate heading (for example "Mercury in glass thermometer transients") on the graph paper.
- Plot the cooling and heating curve on one graph.
- To plot a curve, first put a dot on the graph for each of your data points. Use x's for one set of data (say, the cooling data) and dots with circles around them, ⊙, for the other set of data. (Further sets of data can be distinguished by other symbols such as △, ⊡, etc.)
- Having made individual dots, connect each set of data with a smooth curve. Some dots may not quite be on this curve, but about as many dots should be below the curve as above it.

AN EXPERIMENT .....

..... ON THERMAL TRANSIENTS IN A TRANSISTOR

You will now perform an experiment similar to the one on the previous pages, only this time with the power transistor. The transistor will be supplied with a constant power input, and you will record its temperature (with the thermocouple) at a number of different times. In this way you will find the transient thermal response of the transistor. The graph of this transient response will show a form characteristic of most heating and cooling processes, for example as in the previous thermometer transient.

PREPARATION:

SET UP and check the power transistor circuit as you did in Part I.

CALIBRATE THE METER for the thermocouple. Get an ice water bath, and make sure the thermocouple-meter system is working properly (check 0°C and room temperature).

ATTACH THE THERMOCOUPLE to the transistor, again as in Part I.

PREPARE A DATA TABLE like the one shown at the right. During the first minute, you should take data at 15 sec. intervals. As the temperature increases more slowly, take data at larger intervals. Don't enter all the times now.

t (min.)	Meter Reading (mV)	T (°C)
0		
0.25		
0.5		
0.75		
1.0		
1.5		
⋮		

One person should have a watch with a second hand so that he can take meter readings at the times indicated in the data table. As the experiment proceeds, you will have plenty of time to enter both times and meter readings.

The other person should be ready to *keep the input power constant*. As you saw in Part I, the transistor characteristics change rapidly with temperature, so constant corrections will be needed to keep the current at the correct value.

PROCEDURE

1. QUICKLY SET THE POWER to 6 watts (about 0.5 amps), and then without turning down the current, turn off the power supply.

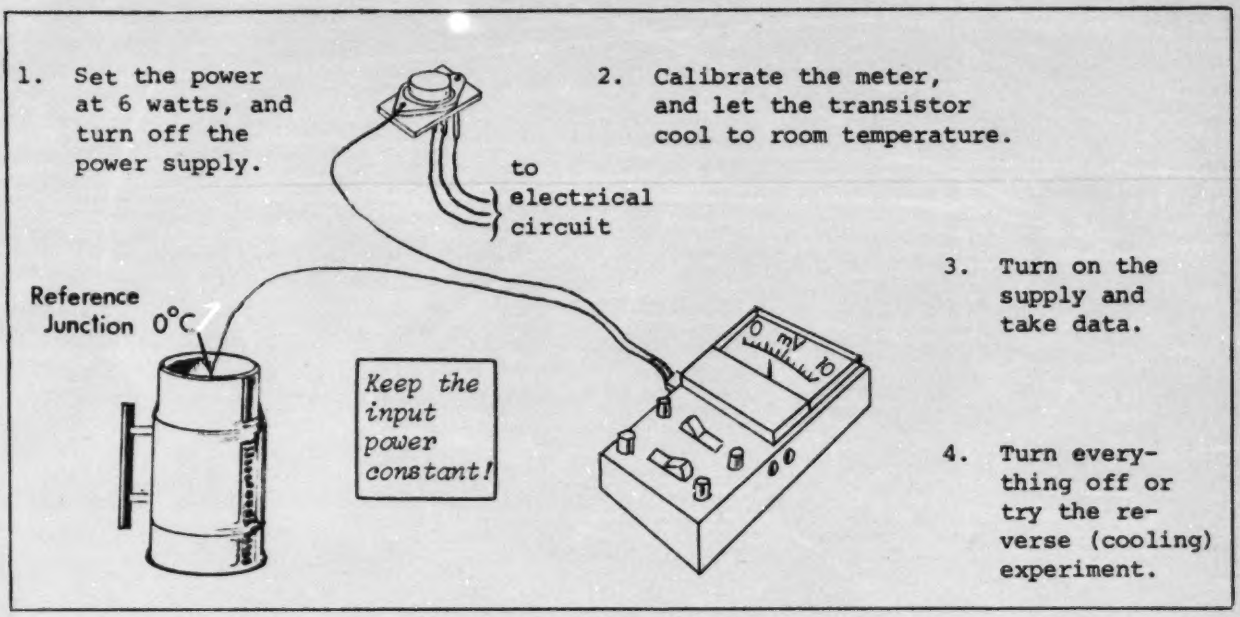
2. CHECK THE THERMOCOUPLE READING, and make sure it corresponds to room temperature. You will probably have to cool down the transistor (wait or use a fan) which may have warmed up a little while setting the power. Record the t = 0 meter reading, and the power setting (6 watts).

3. TURN ON THE POWER SUPPLY and start timing and taking data. Be sure to keep the power constant.

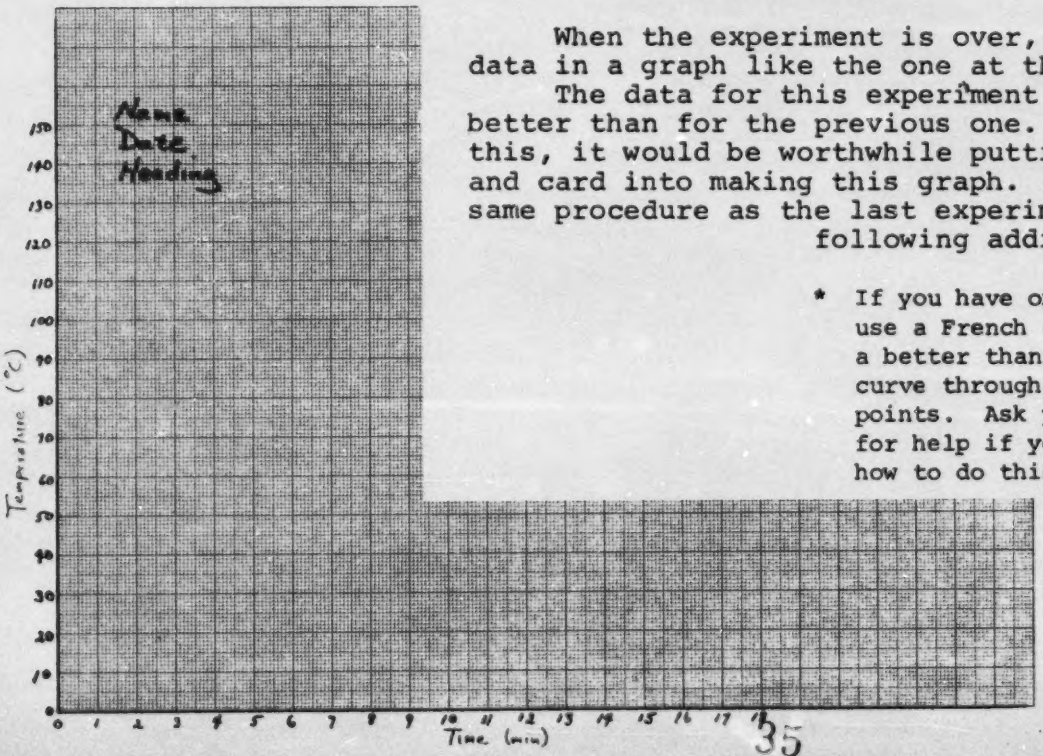
4. When the temperature has leveled off to a fairly constant value, TURN DOWN THE CURRENT AND TURN OFF THE POWER SUPPLY.

OPTIONAL:

You may want to take a cooling curve too. If so, make another column in your data table labeled "Meter Reading: Cooling", and start taking data as soon as you turn off the power. (At t = 0, T = the final rising curve temperature.)


1. Set the power at 6 watts, and turn off the power supply.
2. Calibrate the meter, and let the transistor cool to room temperature.
to electrical circuit
Reference Junction 0°C
Keep the input power constant!
3. Turn on the supply and take data.
4. Turn everything off or try the reverse (cooling) experiment.

GRAPHING THE DATA



When the experiment is over, graph the data in a graph like the one at the left.

The data for this experiment should be better than for the previous one. Because of this, it would be worthwhile putting more time and card into making this graph. Follow the same procedure as the last experiment with the following addition:

* If you have one available, use a French curve to make a better than free-hand curve through your data points. Ask your teacher for help if you don't know how to do this.

CONSERVATION OF ENERGY EXPLAINS TRANSIENT BEHAVIOR IN TRANSISTORS. . .

To understand the nature of transients as explored on the previous pages, it is necessary to know in greater detail just what happens to the energy involved. Which way does it flow? How much energy flows? How is energy related to temperature in various situations? To start to answer these questions, it is necessary to apply an important principle of physics - the conservation of energy.

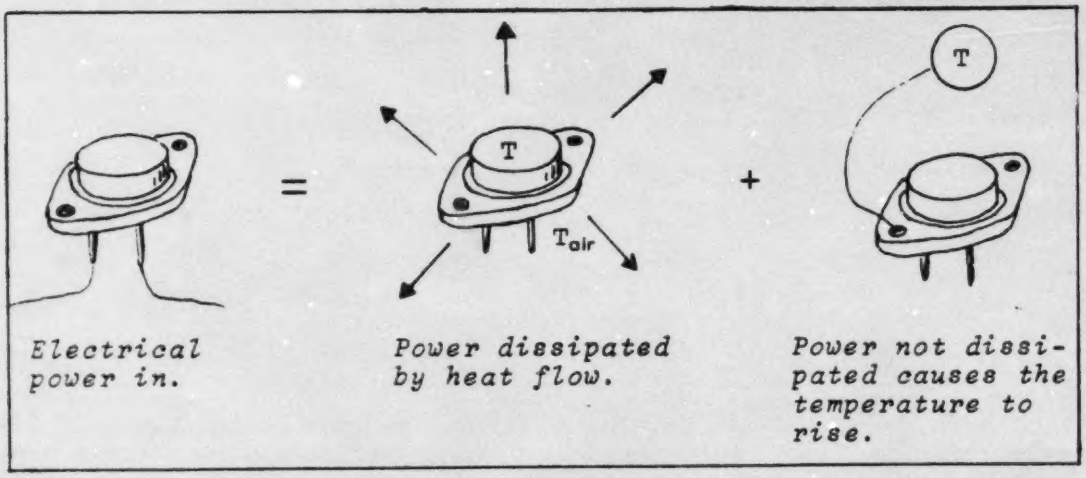
CONSERVATION OF ENERGY AS APPLIED TO THE POWER TRANSISTOR. . .

The law of conservation of energy states that energy is neither created nor disappears, it just changes form. In the power transistor experiments then, *electrical* energy supplied by the power supply to the transistor must all be accounted for. This input energy is partly dissipated by the transistor (changed into *thermal* energy of the surroundings), and partly used to heat the transistor (increasing its thermal energy). Thus we may write the law of conservation of energy for this situation as the following equation:

Energy input in one second = Energy dissipated in one second + Energy left over to heat transistor in one second.

or:

Input Power = Dissipated Power + Power to heat transistor.



Electrical power in.

Power dissipated by heat flow.

Power not dissipated causes the temperature to rise.

To make this a useful formula, it is necessary to have formulas for each of the three terms. Consider first the power input term:

INPUT POWER

This is the simplest of the three to determine. As we saw in part one the input is generated electrically in the power transistor and is simply the product of the voltage, V, and the current I in the collector-emitter part of the circuit. That is the:

$$\textit{Input Power} \quad P_{in} = VI$$

HEATING POWER DETERMINED BY HEAT CAPACITY

The next power in the equation to consider is the power used to heat the transistor.

The *thermal* internal energy of most solids, liquids, and gases is simply a constant times their temperature. This simple rule applies over a fairly large temperature range. This means that to find changes in the thermal energy content of a body when it changes temperature, we just have to multiply the change in temperature by a constant.

(change in thermal energy) = (constant) X (temp. difference);

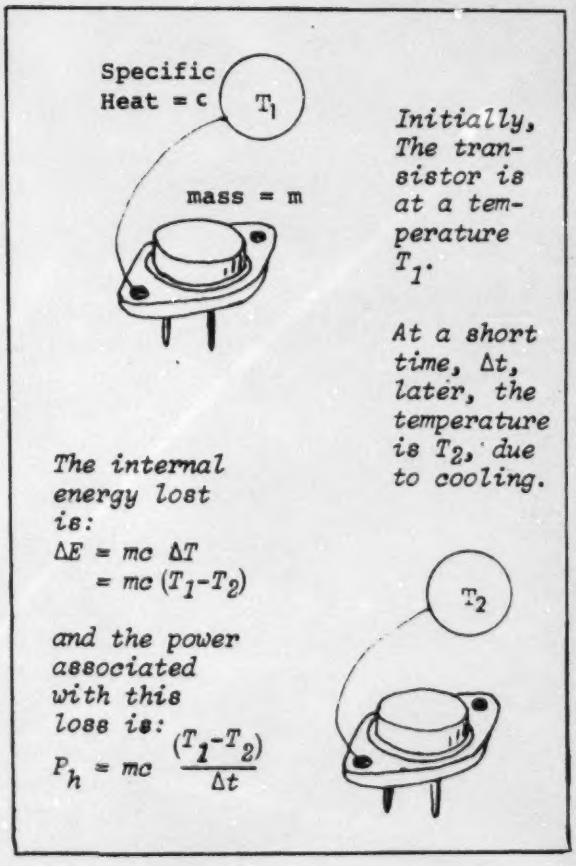
$$\Delta E = C \times \Delta T$$

The constant C is called the *heat capacity* of the substance. It depends on what the substance is, and on how much of the substance there is. If the mass is doubled, so is C. Since C depends on the amount of the substance, it can't be listed in books.

However, another number called the *specific heat*, c, can be and is listed in tables. It is related to the internal energy change resulting from a temperature change by,

$$\Delta E = mc\Delta T$$

where m is the mass of the object in grams and c is the specific heat in joules/gram °C. (Note that C = mc.) The specific heat, c, depends on the substance involved, but very little on the temperature over the temperature range involved in the experiments of this module.


Specific Heat = c
T_1
mass = m
Initially, The transistor is at a temperature T_1.
At a short time, Δt, later, the temperature is T_2, due to cooling.
The internal energy lost is:
$\Delta E = mc\ \Delta T$
$= mc\ (T_1 - T_2)$
and the power associated with this loss is:
$P_h = mc\ \frac{(T_1 - T_2)}{\Delta t}$
T_2

Since power is energy per unit time:

$$P_h = \frac{\Delta E}{\Delta t},$$

the portion of the input power that heats up the transistor is given by:

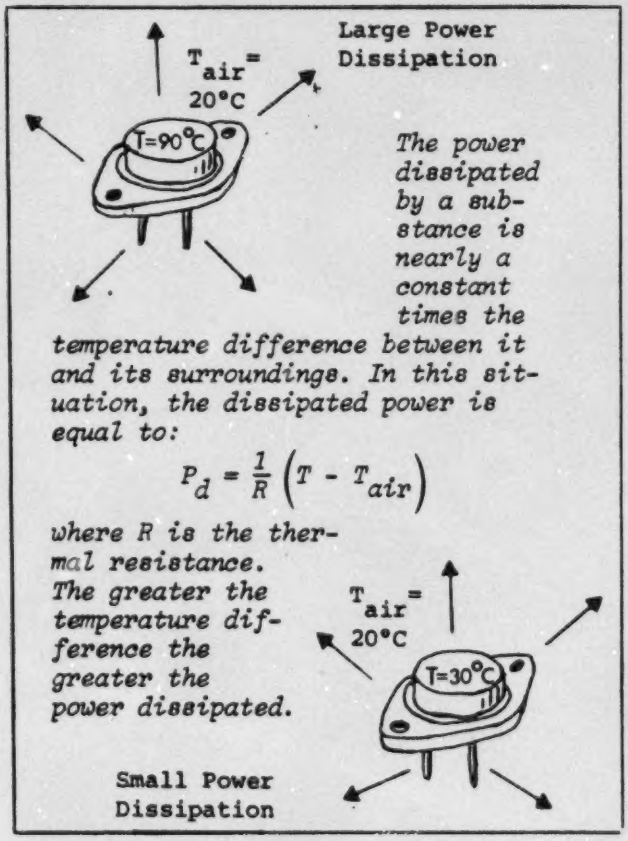
$$\textit{Heating Power} \quad P_h = mc\,\frac{\Delta T}{\Delta t}$$

where Δt is the time in seconds during which the temperature change ΔT takes place, and P_h is the power used for heating in watts. If ΔT is negative, the transistor has lost energy and cooled down.

DISSIPATED POWER DETERMINED BY THERMAL RESISTANCE

The power lost or dissipated by a body, such as the transistor or a cup of water, is very nearly proportional to the *difference* in temperature between it and *its surroundings*. This is not the same as the case of the internal energy change, where it was the *change* in temperature of *the body itself* that was important. The dissipated power is thus given by:

$$\textit{Dissipated Power} \quad P_d = \left(\frac{1}{R}\right)\left(T_{body} - T_{air}\right)$$



The power dissipated by a substance is nearly a constant times the temperature difference between it and its surroundings. In this situation, the dissipated power is equal to:

$$P_d = \frac{1}{R}\left(T - T_{air}\right)$$

where R is the thermal resistance. The greater the temperature difference the greater the power dissipated.

The constant, R, is called the *thermal resistance* and is measured in °C/watt. It depends on a large number of things, and will be discussed in Part III. Note that this equation says something about the way heat flows. If the body is warmer than surroundings, P_d is positive and heat flows to the surroundings. If the body is cooler than its surroundings, P_d is negative and the body absorbs heat. In general, heat always flows from hotter to colder regions or bodies. Also, the greater the temperature difference between a body and its surroundings the greater the amount of power that will be dissipated.

THE FINAL ENERGY EQUATION

Putting the above three formulas for power back into the equation for conservation of energy:

$$\text{Input power} = \text{Dissipated power} + \text{Heating power}$$

we get:

The energy conservation equation

$$VI = \left(\frac{1}{R}\right)\ (T - T_{air}) + mc\left(\frac{\Delta T}{\Delta t}\right)$$

This is the equation which predicts both the equilibrium and transient behavior for a simple situation. In this equation m can be determined simply by weighing the body and c can be looked up in a table provided the material the body is made of is known. R on the other hand must in general be determined by experiment though calculations can give an indication of what it will be, as we will show in part three.

FINDING THE THERMAL RESISTANCE:

One way to find R is to put in a constant power to the system (for instance to the transistor), and then wait for the transient to stop. At this point $(\Delta T/\Delta t) = 0$, since the temperature no longer changes, and the above equation then becomes:

$$VI = \left(\frac{1}{R}\right)\ (T_f - T_{air})$$

where T_f is the final temperature of the system.

Solving for R gives:

$$\textit{The thermal resistance } R = \frac{(T_f - T_{air})}{VI}$$

Thus the thermal resistance can be determined for a given situation by measuring the final equilibrium temperature, T_f for some steady power input, VI, and knowing the surrounding air temperature, T_{air}. Once R is found in this way for *one* power input, the energy conservation equation becomes useful for predicting the temperature (equilibrium and transient) for *any* power input.

That is:

$$T_f - T_{air} = R \times VI$$

or:

$$T_f = T_{air} + R \times VI$$

Final equilibrium temperature for any power input VI.

TIME CONSTANTS AND YOUR EXPERIMENTAL RESULTS

TRANSIENT DECAY

What do all the formulas on the previous pages have to do with transient behavior? Can they help us predict anything? One thing they predict is the final temperature for *any* power input, once the thermal resistance for a given situation has been found for *one* power input. This idea will be further explored in Part III. With respect to transients, the major questions of interest are "How long does it take?", and "Can the temperature versus time graph be predicted?"

The simplest case to look at is transient decay, where the transistor or other body starts at a high temperature and the power is turned off.

.....This means that VI = 0, and thus the equation describing the decay is:

dissipated power = Power from cooling transistors

or:

$$\frac{1}{R}(T-T_{air}) = mc\frac{\Delta T}{\Delta t}$$

Since T_{air} does not change the change in the transistor temperature is the same as the change in the temperature difference $(T-T_{air})$:

$$\Delta T = \Delta(T-T_{air})$$

Using this, the equation for decay becomes:

$$-\frac{1}{R}(T-T_{air}) = C\frac{\Delta(T-T_{air})}{\Delta t}$$

where we have returned to heat capacity $C = mc$.

.....Dividing by C and turning the equation around we get:

$$\frac{\Delta(T-T_{air})}{\Delta t} = -\frac{1}{RC}(T-T_{air})$$

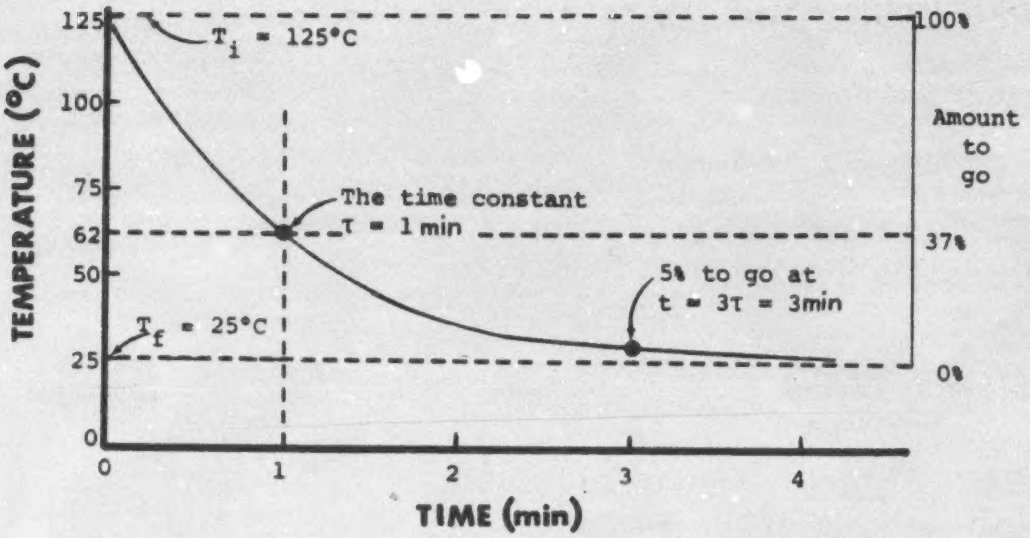
The equation of transient decay.

This equation can be solved. For a discussion of the solution see the optional section on page 43. There it is shown that the solution is an exponential expression for:

Transient temperature decay $\quad (T-T_f) = (T_i-T_f)\,e^{-t/RC}.$

In this expression T is the temperature of the body at any time t after the start of the transient decay, and T_i is the initial temperature of the body before the transient decay began and T_f is the final temperature of the body after the transient is complete, or $T_f = T_{air}$.

A graph of this equation for $T_f = 25°C$, $T_i-T_f = 100°C$, and $RC = 1$ min. is shown on the next page.



Exponential decay is completely described by a time constant, τ, and the initial, T_i, and final, T_f temperatures.

WHAT THE EQUATION SAYS:

There are two very important features of this equation. First it is an equation for the temperature *difference* ($T - T_f$) and secondly, there is the factor RC which is called the *time constant*, τ. The time constant is the time it takes for the temperature difference to reach 37% of its original value.

The Time Constant

Theory: $\tau = RC$

Experiment: τ = "37% to go" point on graph

3τ = "5% to go" point

After a time equal to three time constants has gone by, the cooling process is 95% completed. (See page 44).

Notice that, according to the equation and the graph, the final equilibrium temperature *is never reached.* It is only approached, getting closer and closer as time passes. For most purposes, however, 95% is close enough for you to say that the transient is over. Thus the importance of the time constant is that it gives a measure of how long it takes for a transient thermal change to take place. *If you know the time constant, τ, for a transient thermal process then you must wait at least 3τ before the new equilibrium temperature is reached.*

TRANSIENT GROWTH. . .

Practically everything that has been said about transient decay applies to transient growth as well. The temperature difference is still an exponential when plotted versus time. All you have to do is flip over a decay graph, and it becomes a growth graph, as shown on the page 40. (Your thermometer temperature growth and decay experiment graphs should be "mirror images" of each other.) RC is still the time for the temperature difference to come to 37% of its original value. All that is needed to prove these things is to show that transient growth obeys the same equation as transient decay, except that in the case of growth, it is T_f that is gradually approached instead of T_{air}. This is done in an optional section on page 44 .

INTERPRETING YOUR DATA

The first and easiest thing to do in interpreting your data is to find the thermal resistance from the final temperature using the formula:

$$R = \frac{T_f - T_{air}}{VI}$$

1. CALCULATE R FROM YOUR GRAPH: From your graph of transient thermal growth in the power transistor, determine the final equilibrium temperature, T_f. Using this value, the air temperature surrounding the transistor, T_{air}, and your calculated input power, VI, calculate the thermal resistance for this set-up.

2. DETERMINE THE TIME CONSTANT FOR THE THERMOMETER: The illustration on the next page shows the procedure for determining the time constant from a graph of transient thermal response. Follow the steps to determine the time constant for your thermometer. Do it for both the transient rise and the transient decay curves. How well do the two time constants compare?

3. DETERMINE THE TIME CONSTANT FOR THE TRANSISTOR: Now follow the same steps with your graph of transient thermal growth in the power transistor.

4. COMPARE THE 3τ POINTS FOR EACH OF YOUR GRAPHS: When you have found τ, multiply it by 3. This should give the 5% to go point. Check on your graph the temperature corresponding to the time 3τ. How close is this to 5% of $T_f - T_i$? Mark and label the 5% to go point and the 3τ point on your graph. The usefulness of the time constant is partly that it allows us to predict how long the transient will take: 3τ is a reasonable measure of this time in some cases, though to be certain the transient is over, it would be good to wait a few more time constant periods.

TRANSISTOR THERMAL RESISTANCE

T_f = _____ R = _____

T_{air} = _____

THERMOMETER TIME CONSTANT

warming τ = _____

3τ = _____

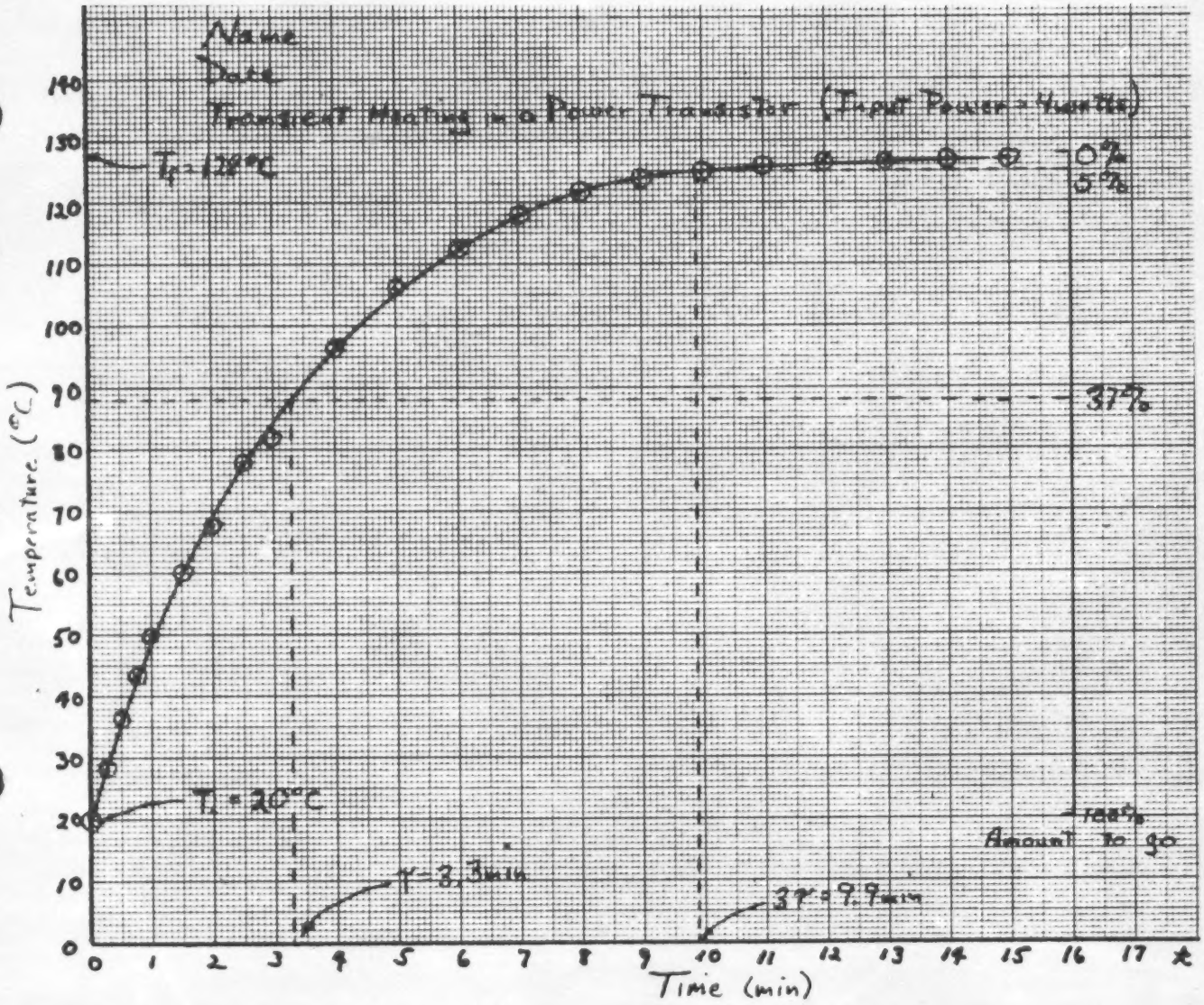
cooling τ = _____

3τ = _____

TRANSISTOR TIME CONSTANT

τ = _____

3τ = _____



HOW TO FIND THE TIME CONSTANT FOR TRANSIENT GROWTH:

1. *To find τ, first find $T_i - T_f$:* $128 - 20 = 108°C$
2. *Multiply this by (0.37):* $(108)(0.37) = 40°C$

   and subtract the result from T_f: $128 - 40 = 88°C$

   This gives the 37% to go point.
3. *Find the time corresponding to this on the graph, as shown:* $t = 3.3$ min.
4. *This time is the time constant:* $\tau = 3.3$ min.
5. *The 5% to go point is found by multiplying $(T_i - T_f)$ by .05:* $(108°)(0.05) = 5°C$

   and subtracting it from T_f: $128° - 5° = 123°$
6. *This should agree with the temperature at 3τ=9.9 min.:* $T = 125°C$

FOR TRANSIENT DECAY: For a decay curve in step 2 *add* the "37% of the difference" value to the final temperature to get the 37% to go point instead of subtracting from T_f. Also do this for the "5% to go point" in step 5.

PREDICTING THE TIME CONSTANT:

As an example of an RC calculation, the transistor in the experiment for which the data are shown has a mass of about 10 grams, and a specific heat of about 0.8 joules/gm°C.

This means that the heat capacity is: $C = mc$

$= (10\ g) \times (0.8\ \text{joules/gm°C})$

$= 8\ \text{joules/°C}$

.....The thermal resistance for the situation was: $R = \frac{T_f - T_{air}}{VI}$

$= \frac{108°C}{4\ \text{watts}}$

$= 27°C/\text{watt}$

Thus the time constant: $\tau = RC$

is: $\tau = (8\ \text{joules/°C}) \times (27°C/\text{watt})$

$= 216\ \text{sec.}$

$= 3.6\ \text{min.}$

This number is in good agreement with the experimentally determined value of 3.3 min.

CALCULATE τ FROM YOUR VALUE OF R: Use your value of R to calculate τ. How well do your experimental and theoretical τ values agree?

THERMOMETERS REVISITED

—OR—

WHY THE MERCURY THERMOMETER WAS LOW AND SLOW

INTRODUCTION

As a final look at transients, let us reconsider the problem discussed in Part I - how "good" is a thermometer? The idea of thermal resistance makes it possible to discuss this question in greater detail.

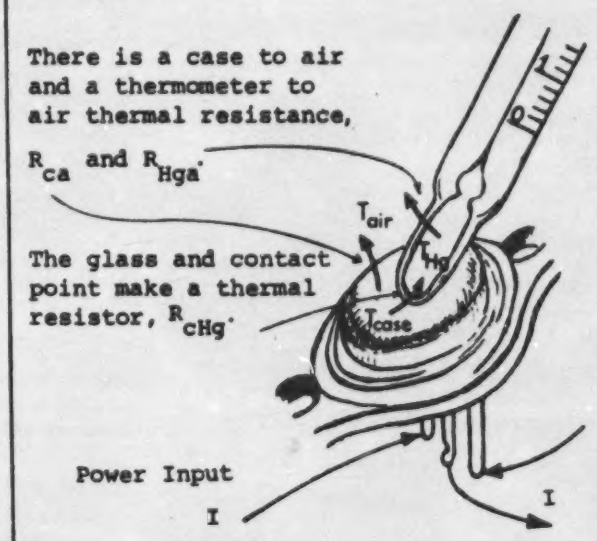
To begin with, to "simply" put a thermometer on a hot transistor is really to create quite a complicated situation. In the illustration on the next page, the heat flow paths and thermal resistances are shown. The electrical current provides a source of energy which heats the transistor, the surrounding air, and the thermometer. Heat flows from the transistor to the air, and through the glass to the mercury, as well as from the mercury to the air through the glass.

Each of the heat flow processes has a thermal resistance associated with it; there is a resistance from the transistor case to the air, from the case to the mercury, and from the mercury to the air.

WHY WAS IT LOW?

There are two main things which make the thermometer read perhaps as much as tens of degrees low. One thing is that the thermometer decreases the "effective" thermal resistance from the case to the air, thus lowering T_f. That is, $T_f = R(VI) + T_{air}$: for a given power, VI, and T_{air}, a lower R means a lower T_f. A more important effect is that when heat flows through the glass to the mercury, there is a temperature drop. $T_{case} - T_{Hg} = RP$, where P is the heat flowing per second to the mercury. This is like an "IR" voltage drop across an electrical resistor. (V = IR: Ohm's Law). Thus, the thermometer lowers the case temperature a little, and further, the mercury which measures the temperature is cooler than the case.

The reading is low because there is a PR temperature drop, and because T_f is lowered by the thermometer.


There is a case to air and a thermometer to air thermal resistance, R_{ca} and R_{Hga}.
The glass and contact point make a thermal resistor, R_{cHg}.
T_{air}
T_{Hg}
T_{case}
Power Input
I
I

The time constant of the mercury thermometer isn't small enough compared to that of the transistor. Thus it can't keep up to the transistor temperature variations. It should be smaller (C smaller), and make better thermal contact (R smaller), to make $\tau = RC$ Smaller.

WHAT IS "TOO SLOW" AND WHAT CAN BE DONE ABOUT IT?

There are two important transients and time constants in this thermal system, that of the transistor, and that of the thermometer. Ideally, the thermometer should have $\tau = 0$ sec., but this is not possible. The best that can be done is to make the mass as small (lower mc) and the thermal contact as good (lower R) as possible within the limits and needs of the experiment. In this case, *what is needed is a thermometer with a time constant much smaller than the constant of the transistor.* The thermocouple's few second response time provides this. The mercury thermometer's tens of seconds response time is fine for measuring room or outside temperatures where the temperature takes many minutes or even hours to change by very much, but it can't keep up with the transistor temperatur changes.

Note that the thermometere responds more slowly to air temperature changes than to water temperature changes (try it!), but it still is fast enough for everyday use. The difference between the air and water cases is due to a difference in R.

OPTIONAL TOPICS:

THE EXPONENTIAL. . .

....The general heat flow equation $\frac{\Delta x}{\Delta t} = -\frac{x}{RC}$ (x = a temperature difference)

has an *exponential* as its solution $x = x_0 e^{-t/RC}$

What does this mean?

.....To raise a number to the n^{th} power means to multiply it by itself n times.....

$$\begin{cases} a^0 = 1 \\ a^1 = a \\ a^2 = a \cdot a \\ a^3 = a \cdot a \cdot a \\ a^n = a \cdot a \cdot a \cdot \ldots \cdot a \text{ (n factors)} \end{cases}$$

The letter e stands for a number $e = 2.72$ (approximately)

This number, too, can be raised to powers.

$$\begin{cases} e^0 = 1 \\ e^1 = 2.72 \\ e^2 = (2.72)(2.72) = 7.39 \\ e^3 = 20.1, \text{ etc.} \end{cases}$$

Negative powers are just 1 over the positive power

$$\begin{cases} a^{-1} = \frac{1}{a} \\ a^{-2} = \frac{1}{a^2} \\ a^{-3} = \frac{1}{a^3}, \text{ etc.} \end{cases}$$

Of course, e can be taken to negative powers.

$$\begin{cases} e^{-1} = \frac{1}{e} = \frac{1}{2.72} = 0.368 \\ e^{-2} = \frac{1}{e^2} = \frac{1}{7.39} = 0.139 \\ e^{-3} = 0.05, \text{ etc.} \end{cases}$$

Non-integer powers of e, or any other number are hard to calculate, but such powers of e are given in tables.

$$\begin{cases} e^{2.53} = (2.72)^{2.53} = 12.6 \\ e^{-3.2} = 0.041 \\ e^{-9.1} = 0.00011 \end{cases}$$

When the time is 0, the value of x is x_0

$$x = x_0 e^{-t/RC}$$

At $t = 0$,

$$x = x_0 e^0$$

$$= x_0$$

After one time constant period, the temperature difference, x, has gone down to 37% of initial value. This is the "37% to go" point.

At $t = RC$ (that is, $t = \tau$),

$$x = x_0 e^{-RC/RC}$$

$$= x_0 e^{-1}$$

$$= (0.37)x_0$$ or 37% of the initial value

After three time constant periods, the "5% to go" point is reached.

At $t = 3RC$,

$$x = x_0 e^{-3}$$

$$= (0.05)x_0$$ or 5% of the initial value

EQUATION OF EXPONENTIAL GROWTH

The claim was made on page 38 that exponential growth obeys the same equation as that for exponential decay. This is verified by the following derivation. For transient growth (from page 36) we have:

the conservation of energy equation:

$$VI = \left(\frac{1}{R}\right)(T - T_{air}) + C\left(\frac{\Delta T}{\Delta t}\right)$$

and the equation for the final equilibrium temperature:

$$T_f = R(VI) + T_{air}$$

We can rewrite the second equation:

$$VI = \frac{T_f - T_{air}}{R}$$

and put it back into the first equation:

$$\frac{T_f - T_{air}}{R} = \frac{(T - T_{air})}{R} + C\left(\frac{\Delta T}{\Delta t}\right)$$

The $\frac{T_{air}}{R}$ terms balance out giving:

$$\frac{T_f - T}{R} = C\left(\frac{\Delta T}{\Delta t}\right)$$

Since T_f is a constant we may write:

$$\Delta T = \Delta(T - T_f)$$

$$= -\Delta(T_f - T)$$

Putting this into the above equation gives:

The equation of transient growth $$\frac{\Delta(T_f - T)}{\Delta t} = -\frac{1}{RC}(T_f - T)$$

This equation can be solved as in the previous discussion. The solution is the exponential expression for:

Transient temperature growth $(T_f - T) = (T_f - T_i)e^{-t/RC}$

In this equation (T_f-T_i) is the difference between the initial and final temperatures, that is the "amount to go" for the temperature. At $t = 0$, $T = T_i$ and as time passes, the *difference* between the actual temperature and the final temperature (T_f-T), gradually decreases (or decays) with a time constant $\tau = RC$. Thus transient growth is simply a transient decay of the "amount to go," T_f-T_i.

Review

SUMMARY

A *transient* is a change that takes place in a fairly short time between *equilibrium* states. An equilibrium state is one in which there is no observable change in the state of a system with time.

The experiments of this section showed that for simple thermal situations, transients in *temperature* take place in a way described by *exponentials*.

Transient decay and *transient growth* curves are "mirror images" of each other. The exponential form of the curves is the same.

Conservation of energy, that is, the fact that energy changes form but doesn't disappear, makes it possible to predict what the transient behavior of a thermal system is, that is:

input power = dissipated power + heating power

the formula for *input power* is: $P_i = VI$

the formula for *dissipated power* is: $P_d = (\frac{1}{R})\ (T - T_{air})$;

and the formula for *heating power* is: $P_h = mc(\frac{\Delta T}{\Delta t})$

Putting these three together gives the conservation equation: $VI = \frac{1}{R}\ (T - T_{air}) + C(\frac{\Delta T}{\Delta t})$

From this equation we can get an expression for experimentally determining the *thermal resistance*: $R = \frac{(T_f - T_{air})}{VI}$

and, knowing the thermal resistance, for the final equilibrium temperature for any power input: $T_f = T_{air} + R \times VI$

The *time constant*, equal to RC, is an important number in the exponential solution to the above equation. It is equal to the time at which the temperature difference is equal to 37% of its original value. 3RC is the "5% to go" point. The time constant is the same for both transient decay and transient growth and is a measure of how long it takes for a thermal transient to take place.

The time constant helps us understand thermal contact and thermometers: if R is low, thermal contact is good; if RC is low for a thermometer in a given situation, the thermometer will have a fast response time.

QUESTIONS

1. a) Why does a mercury thermometer respond so much more slowly in air than in water?

   b) If the resistance from the mercury thermometer to its surroundings could be made equal to zero, the thermometer would still take time to respond. Why is this? Is the same thing true of thermocouples? Why or why not?

2. a) What would the equation for heat flow be if the power transistor were put in a box that didn't let any heat flow out of it?

   b) What would happen to the temperature of the transistor if a constant electrical power was put into it? (You don't have to solve the equation unless you want to).

   c) If the power is turned off at some point, what is the heat flow equation, and what happens to the temperature?

   d) What is the best example you can think of for an "insulating box" such as the one described above? (There aren't any perfect ones: why not?).

3. Isn't there a "PR" drop in temperature when a mercury thermometer is used to measure water temperature, just as there is in measuring transistor temperature? If there is, then why is the mercury thermometer so much more accurate in the case of water?

PROBLEMS

1. A beaker of 750 grams of water is heated on a burner which supplies an input power of 1000 watts. How long will it take to boil the water if it starts at 20°C? (The specific heat of water is 4.2 joules/gm°C).

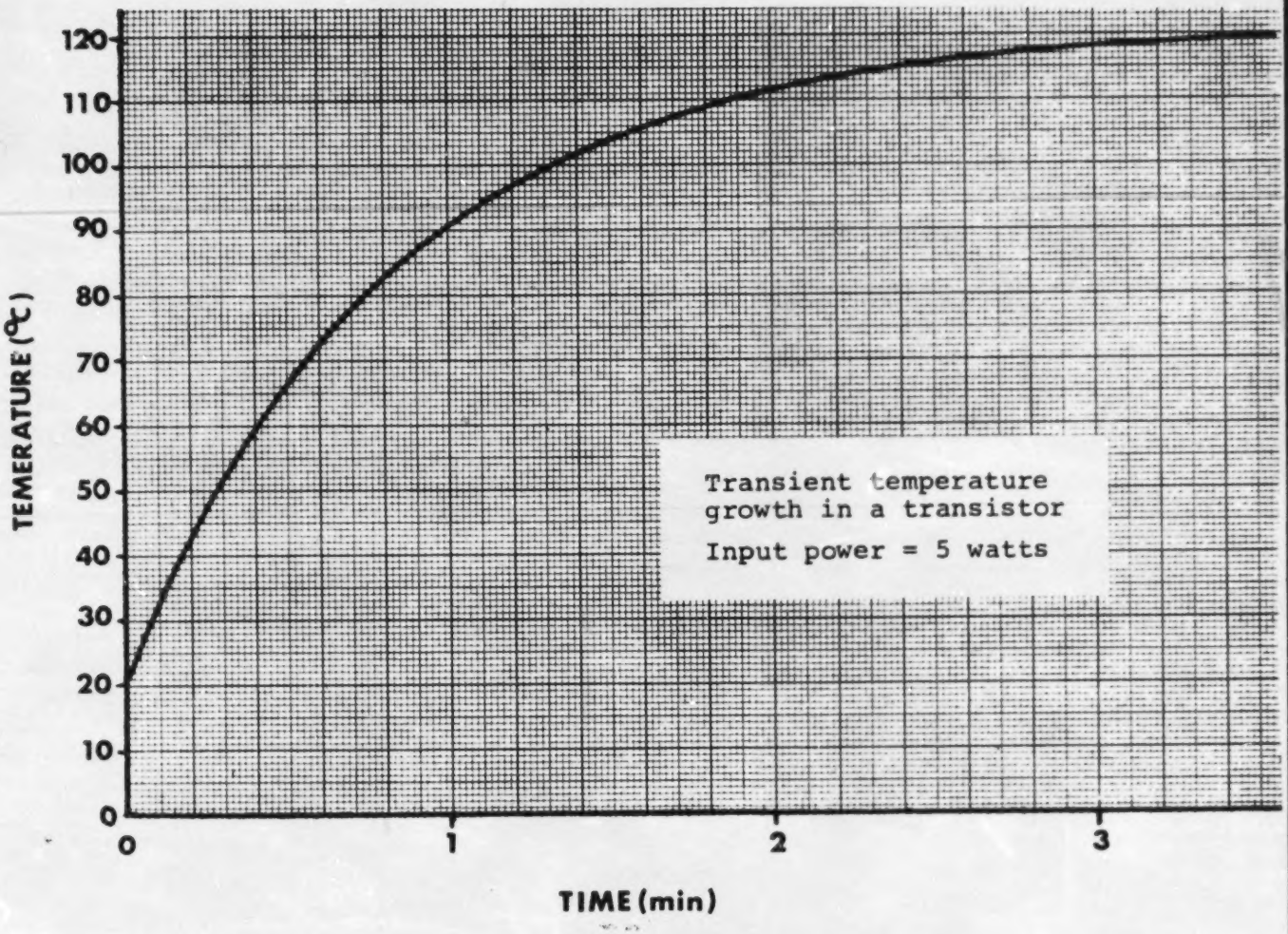
2. A cup of coffee (about 500 gms, with a specific heat about the same as water), in a particular situation, took half an hour to cool to nearly room temperature.

   a) Estimate the time constant for this process.

   b) Using this, determine the thermal resistance between the coffee and its surroundings.

3. If a transistor is supplied with an input power of 3 watts, and the thermal resistance from the case to the air is 5°C/watt, what will the final temperature of the transistor be in a room at 30°C?

4. a) Given the transistor experiment graph on the next page, find the time constant for this particular situation.



b) Draw the graph of what would happen if the power were suddenly turned off, starting with T = 120°C at t = 0.

c) What is the thermal resistance for the situation for which the graph was made?

d) What would T_f be if P = 7 watts?

HEAT TRANSFER PROCESSES

INTRODUCTION

The thermal resistance in a given situation is in part what determines the time constant and final temperature. This means that one way to control τ and T_f is to change the thermal resistance. To do this, it will help considerably to know what the resistance depends on for the three major heat transfer processes - *conduction*, *convection* and *radiation*. What do these terms mean?

If a metal rod is heated at one end, it gets warm at the other end. This is due to *conduction*. No mass moves, but thermal energy flows down the rod.

When a wind blows across your face, you usually feel cooler. Heat is being taken away by the air moving by. This is an example of *convection*. In convection, a moving fluid absorbs energy and carries it away.

Even when there are no objects or fluids around to conduct or convect heat, heat can move from place to place. The sun heats the earth through the nearly perfect vacuum of space. It *radiates* a great amount of heat due to its high temperature. In radiation, heat is transferred by electromagnetic waves such as visible or infrared radiation.

EXAMPLES OF TRANSFER PROCESSES

One place where the equilibrium temperature must be carefully controlled is in the operation of an automobile. In most cars the engine is mainly cooled by a liquid cooling system, though some cars rely only on air. In either case, the portion of the heat generated in the cylinders that is not used to do work in making the car move is conducted through the cylinder walls, and is convected away by a fluid. In the case of the water-cooled engine, the heated water flows to a radiator where the heat is convected away by the air. The air is blown by a fan as well as by the "wind" that the car feels when it moves. This process, as well as a few others, is illustrated on the next page.

The thermal resistance from an automobile engine to the air is hard to calculate, but it is useful to know what processes are taking place, and what factors affect the thermal resistance for each of them. This knowledge aids in the design of cooling and heating systems of all sorts, not only in automobiles.

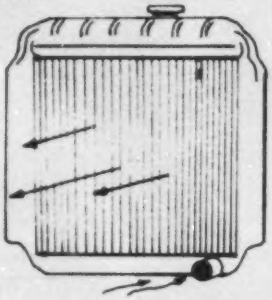
The Automobile Engine:

H_2O cools the cylinder by carrying away heat by *convection*.

Energy Input:
The spark ignites the air - gasoline mixture which has been compressed by the piston: chemical energy and the work done by the piston in compression are the energy inputs.

Hot gases escape in the exhaust stroke; this, like the water cooling, is *convective* cooling.

Heat must be *conducted* through the cylinder walls to get to the water.

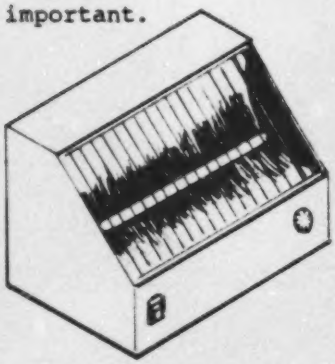


In the car radiator, heat from the hot water is *conducted* through the metal, and then is carried away by *convection;* the air flowing by carries away heat. Some *radiation* also occurs, but this is less important in this case than it is, for instance, in a toaster. (The "radiator" should really be called a "convector.")

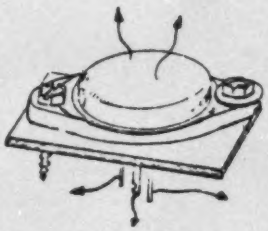
The Space Heater:

A space heater *radiates* heat and uses a fan to improve heat transfer by *convection*. *Conduction* through the air adds only a very small amount to the heat transfer.

When a heating element glows, *radiation* is important.



The Power Transistor:



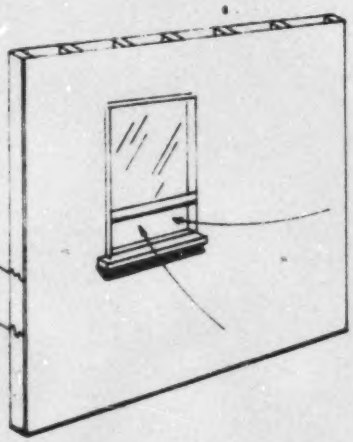
In the case of the power transistor, *conduction* occurs through the case to the outer surface. There, *radiation* and *convection* take heat away; a small amount of heat is conducted away also. *Conduction* through the leads can also be an important heat transfer process.

Houses:

The sun's rays transfer heat to the house by *radiation*, mainly through the windows.

The air moving through the open windows or "leaky" areas of the house transfers heat by *convection*.

On a hot day, heat is *conducted* into the house through the walls. On a cold day, the transfer goes the other way.



FOUR HEAT TRANSFER EXPERIMENTS

INTRODUCTION:

The following experiments show how various changes, such as adding a heat sink or a fan, can change the case to air thermal resistance and thus the ability of the transistor to dissipate heat. At the same time you will see an example of a *non*-exponential transient.

I. TRANSISTOR ALONE

Purpose:

In this experiment you will determine how the temperature varies around the transistor. This information should suggest the various paths in which heat is flowing out of the transistor. From your experiment you should be able to determine which of the heat transfer processes is most important in this situation.

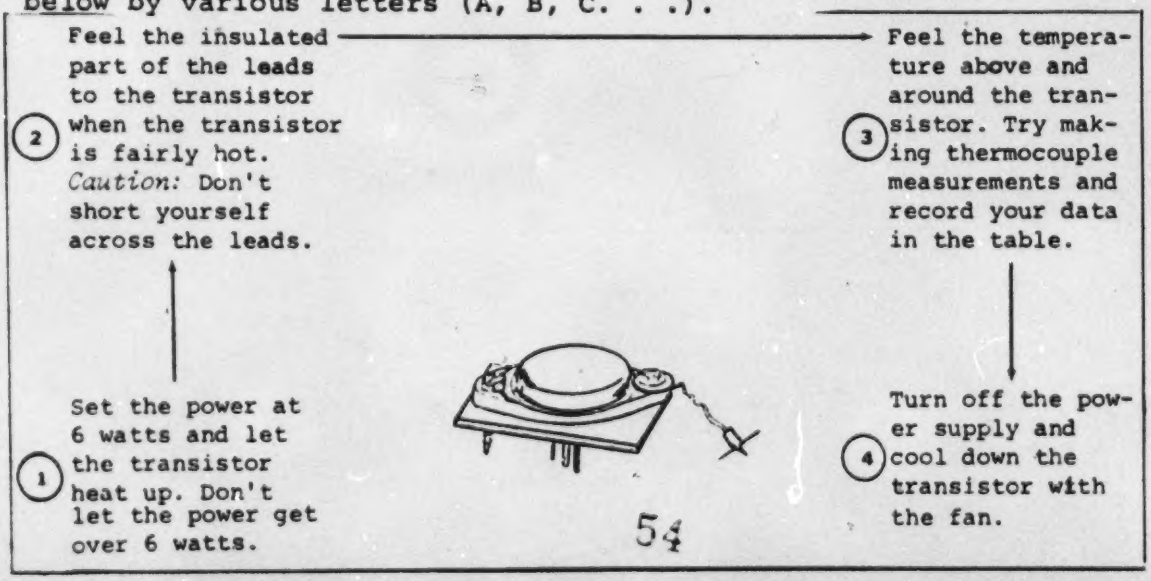
Preparation:

* Set up the transistor circuit as before.
* Prepare an ice water bath for the thermocouple reference junction.
* Calibrate the meter and check that the thermocouple is working properly, (find room temperature).

Position	Distance from transistor	Meter Reading (mV)	Temp. (°C)

Procedure:

Follow the steps given in the illustration below. To make temperature measurements in step 3, detach the thermocouple from the mounting screw and locate it various distances and directions from the transistor. If you try this, record your data in the table. Label your measurement positions on the illustration below by various letters (A, B, C. . .).


(2) Feel the insulated part of the leads to the transistor when the transistor is fairly hot. Caution: Don't short yourself across the leads.
(3) Feel the temperature above and around the transistor. Try making thermocouple measurements and record your data in the table.
(1) Set the power at 6 watts and let the transistor heat up. Don't let the power get over 6 watts.
(4) Turn off the power supply and cool down the transistor with the fan.

II. TRANSISTOR WITH FAN

Purpose:

As we saw in Part II, one power and T_f point can be used to determine R. Once R is found, T_f for other powers can be predicted. Here you will explore this experimentally. As you will see, R, and thus T_f, can be changed considerably by moving the fan around.

Procedure:

Reattach the thermocouple back to the transistor case and follow the steps shown in the illustration.

The transients are quite short in this experiment, so you should have time to try a number of power levels in step 5. Record your data and calculations for at least a few points.

Step

2. Response Time = _____

3. R = _____

   $\tau = RC$ = _____

4. New R = _____

5.

Power	T_f predicted	T_f actual

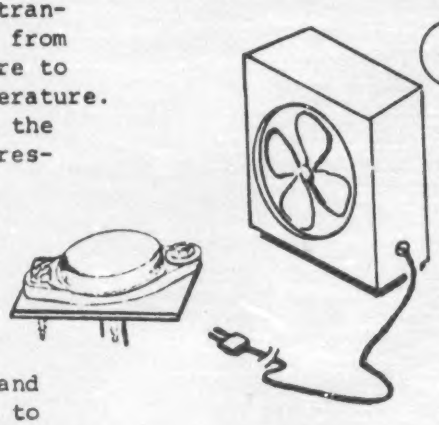
(1) Start the fan and bring it close to the transistor. Turn on the power and set it to 12 watts, and then turn the power off again.

(2) Time how long it takes for the transistor to come from room temperature to its final temperature. Record this in the table as the "response time."

(3) Calculate R, using $R = \frac{T_f - T_{air}}{VI}$ and record it. Recall, from Part II, that for the transistor, C = $\frac{8 \text{ joules}}{^\circ C}$. Calculate $\tau = RC$ and enter it in the table. Is your answer reasonable?

(4) Move the fan back about a foot from the transistor, keeping the power at 12 watts. What happens to T? Calculate the new R and record it.

(5) Move the fan back to its original position. Choose some other power power <u>less than 25 watts!</u> and predict T_f using your results from step 3. How close is the actual T_f to this? Fill in the table with your values.



III. TRANSISTOR WITH HEAT SINK

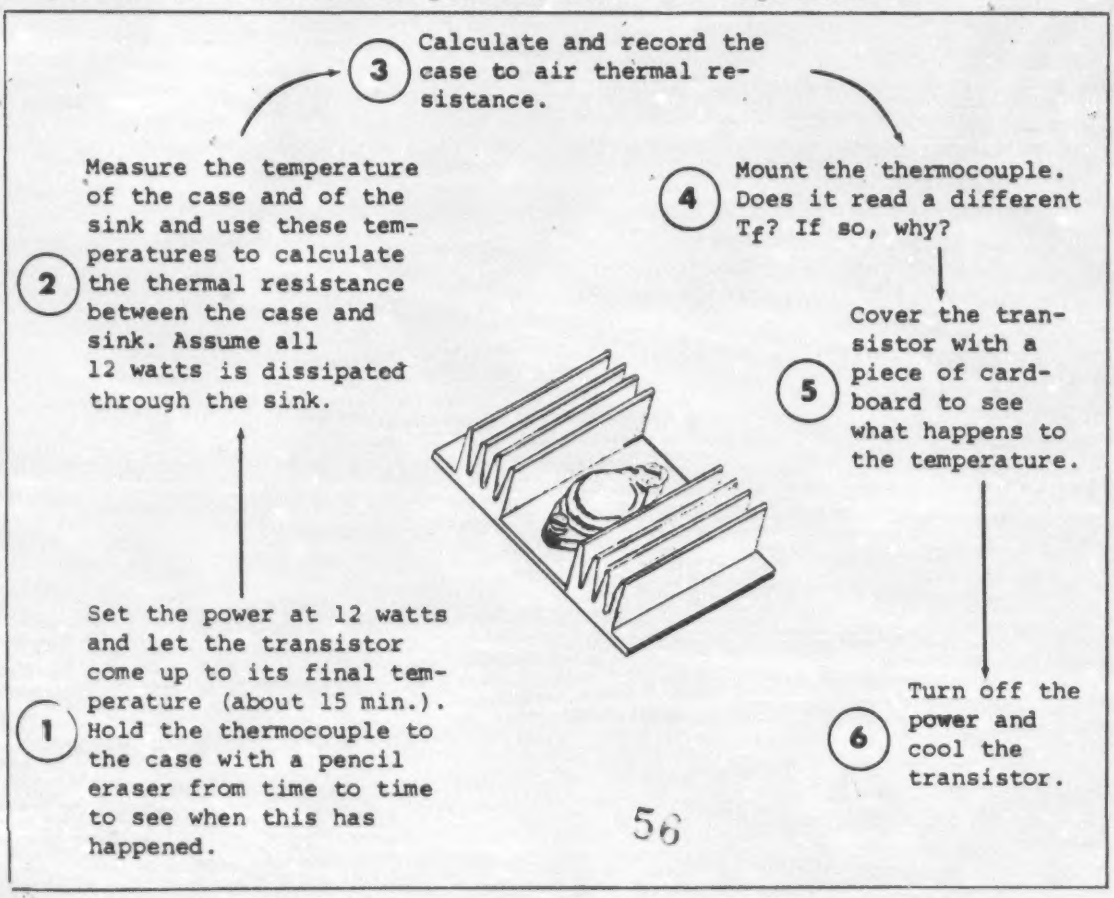
Purpose:

Here you will measure the thermal resistance for the case of a transistor with a heat sink. A heat sink is a device specifically designed to lower the thermal resistance of the transistor to the air and thus improve heat dissipation. Its design is based on optimizing each of the heat transfer processes. In the experiment see if you can see where each comes into play.

Step	Data
2.	T_{case} = _____ T_{sink} = _____ R_{cs} = _____
3.	R_{ca} = _____

Preparation:

Putting the transistor on the Heat Sink: Take the transistor *completely* off the small mounting base. Do this with the power supply turned off. Put the transistor through the holes in the sink, and into the small mounting base again. Put the screws back in, but don't mount the thermocouple yet. If the screws won't go in, the mounting base is probably attached to the transistor in the wrong way. To correct this, take the base off and put it back on the only other way it will go. Then put the screws in and proceed with the experiment.


3 Calculate and record the case to air thermal resistance.
2 Measure the temperature of the case and of the sink and use these temperatures to calculate the thermal resistance between the case and sink. Assume all 12 watts is dissipated through the sink.
4 Mount the thermocouple. Does it read a different T_f? If so, why?
5 Cover the transistor with a piece of cardboard to see what happens to the temperature.
1 Set the power at 12 watts and let the transistor come up to its final temperature (about 15 min.). Hold the thermocouple to the case with a pencil eraser from time to time to see when this has happened.
6 Turn off the power and cool the transistor.

IV. TRANSISTOR WITH HEAT SINK AND FAN

Purpose:

In the first part of this experiment, you will take transient heating data on a transistor with a heat sink and a fan. The plot of the data should have a shape which is similar to, but not the same as, the curves for the experiments in Part II.

In the second part of the experiment, you will explore ways to lower the thermal resistance from the transistor to the air.

Step	Data	
	Situation	R
4.		

Procedure:

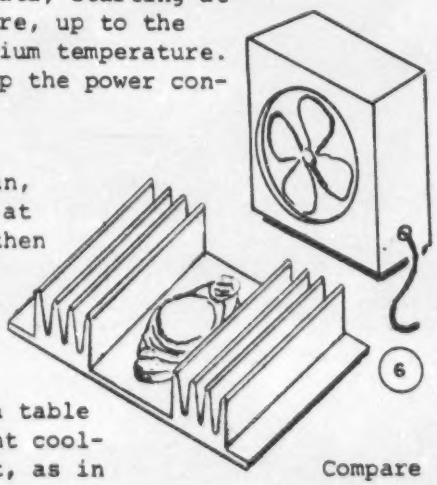
Proceed as shown in the illustration.

In step 4, try to find other ways to lower R than those suggested.

In step 7, find τ using the 37% method. See if 3τ is the "5% to go" point. In situations where the response is not exponential the use of the term "time constant" to describe the behavior isn't exactly valid. Instead words such as *response time* (the time it takes for the system to go completely between equilibrium states), and *rise time* (the time between the "90% to go" and "10% to go" points) are used to describe how long the transient takes. In Parts I and II thermometers were characterized by their response times, which is a useful number whether or not the thermometer behaves exponentially. In non-exponential situations the concept of thermal resistance is still valid, it is just that more than one mass is involved, making the situation more complicated.

TRANSIENT BEHAVIOR

CHANGING R



(1) Prepare a data table for a transient cooling experiment, as in Part II, except take data every 10 seconds.

(2) Turn on the fan, set the power at 30 watts and then quickly turn off the power.

(3) Take heating data, starting at room temperature, up to the final equilibrium temperature. Be sure to keep the power constant.

(4) Try different orientations of the fan to see if you can reduce R and thus T_f. You might try some "thermal joint compound" between the transistor and sink to improve the heat dissipation.

(5) Turn off the power and let the transistor cool.

(6) Plot the transient heating data in the way suggested in Part II. Use scales that let the data completely fill the graph.

(7) Compare this curve to the *exponential* curve of Part I. Are they the same? (This shows that complex thermal systems can't be described by one time constant. The behavior is that of a *sum* of exponentials).

CONDUCTION, CONVECTION, and RADIATION. . .

INTRODUCTION

In the next few pages each of the three major heat transfer processes will be discussed in terms of the four experiments of this section. Conduction will be considered first, since it is important in all of the experiments, and since convection involves conduction.

CONDUCTION:

A DEFINITION OF CONDUCTION:

Let's begin with a precise definition: *Conduction* is the process in which *only* thermal energy is transferred from one place to another through a body or fluid. There is no net motion of the masses involved.

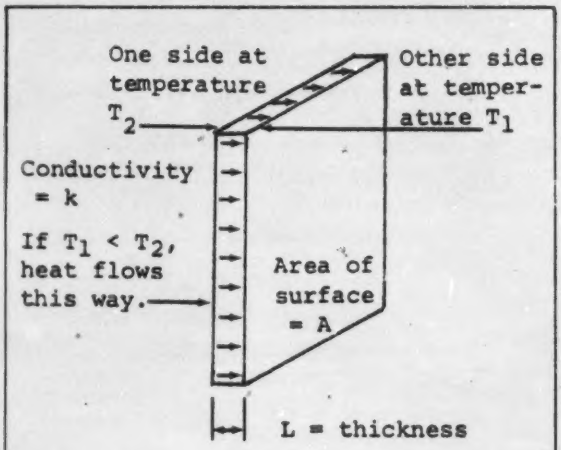
THERMAL RESISTANCE AND CONDUCTION

The thermal power transferred by conduction can be calculated quite easily for the simple case of a slab of material which has a uniform temperature T_1, on (not near) one side, and T_2 on the other side. Assuming losses from the edges are unimportant, the power conducted through such a slab of area A is: $P = \frac{kA}{L}(T_2 - T_1)$.

Remember from Part II that: $P = (\frac{1}{R})(T_2 - T_1)$.

Comparing the two expressions we see that we may define

The thermal resistance for Conduction	$R_{cond} = \frac{L}{kA}$


One side at temperature T_2
Other side at temperature T_1
Conductivity = k
If $T_1 < T_2$, heat flows this way.
Area of surface = A
L = thickness

The heat per second conducted through the slab is:

$$P_c = \frac{kA}{L}(T_2 - T_1)$$

since $P = \frac{1}{R}(T_2 - T_1)$, *and*

$$R_{cond} = \frac{L}{kA}$$

Here k is a constant for a given material called the *thermal conductivity* measured in watts/cm°C if L is measured in cm and A in cm^2. In general the thermal conductivity varies only slightly with temperature. A short table of values for k is given on the next page.

The formula for R_{cond} in this special case points to some general conclusions. Power is transferred more slowly through thick walls than through thin ones. Walls or layers of fluid with a large area, A, for heat to flow through dissipate heat well. Lastly, to get the best heat transfer, it is important to use materials of good thermal conductivity, k. All three of these factors can often be controlled

in a given situation. In the case of the power transistor, a heat sink with a large area and a good thermal conductivity was added to the transistor case to increase the heat dissipation.

WHAT HAPPENS AT BOUNDARIES

The top of the transistor touches the air, and in experiment III, the bottom of the transistor touched the heat sink. Just as in an electrical circuit, there is a *contact resistance* at any such boundary, since the contact is not perfect. These resistances make it harder for heat to flow. The main problem is that the surfaces in contact with each other aren't perfectly smooth, and thus their area of contact is small. This small A means a large R. A can be increased by pushing the surfaces together harder, thus filling in the spaces at the surface. This squeezing process also lowers R by decreasing L. Another way to lower the case-sink resistance is by the use of thermal joint compound, as was suggested in experiment IV. This also fills in "cracks" and thus increases the A for conduction.

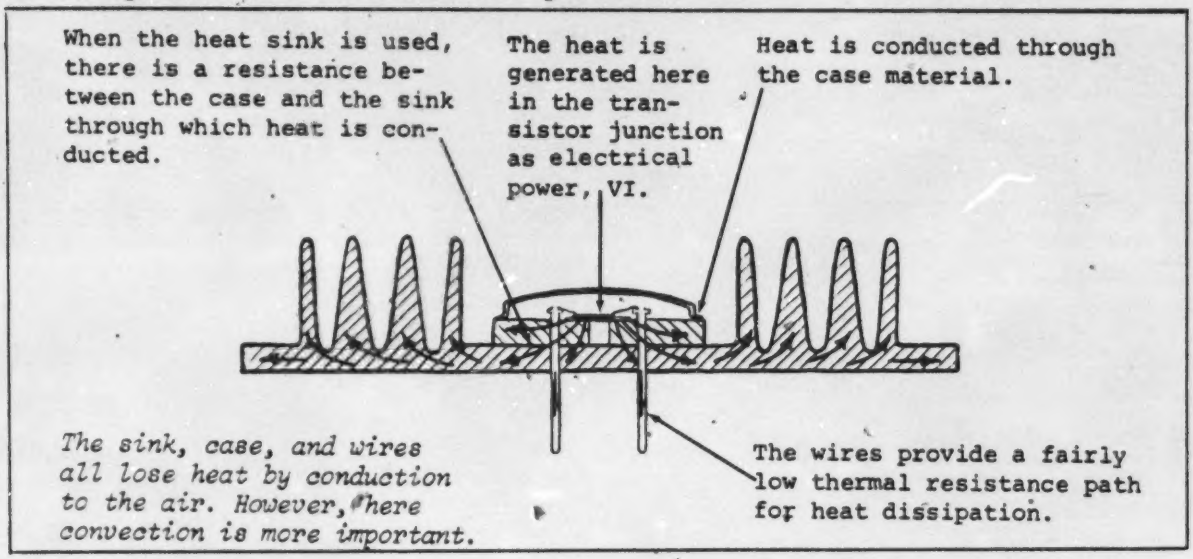
TABLE OF THERMAL CONDUCTIVITIES

Thermal Conductivity k ($\frac{watts}{cm°C}$)	Material	Equivalent Lengths for the same Thermal Resistance
.00069	Air	
.0059	Water	
.0063	Brick	
.01	Glass	the Bars below reduced in length by 10x
	Glass	
.482	Steel	
1.09	Brass	
2.01	Aluminum	
3.85	Copper	

THE IMPORTANCE OF AIR: You can see from the table that air is one of the poorest thermal conductors. One millimeter thickness of air has the same conductivity (for a given area) as one meter of the average metal. Air is important therefore when it surrounds a good conductor, such as the heat sink. In this case, though the heat is conducted easily to the surface of the metal, it must then pass through the air to be dissipated. This makes R much larger than it would be if the metal dissipated the heat, say, into a tub of water (water has a much larger conductivity than air).

HEAT CONDUCTION IN THE TRANSISTOR

The cross section of the transistor shown below indicates the various heat conduction paths important in the experiment. Notice that the leads must also be considered, particularly since two of them go directly to the *hot* transistor juntion.


When the heat sink is used, there is a resistance between the case and the sink through which heat is conducted.
The heat is generated here in the transistor junction as electrical power, VI.
Heat is conducted through the case material.
The sink, case, and wires all lose heat by conduction to the air. However, here convection is more important.
The wires provide a fairly low thermal resistance path for heat dissipation.

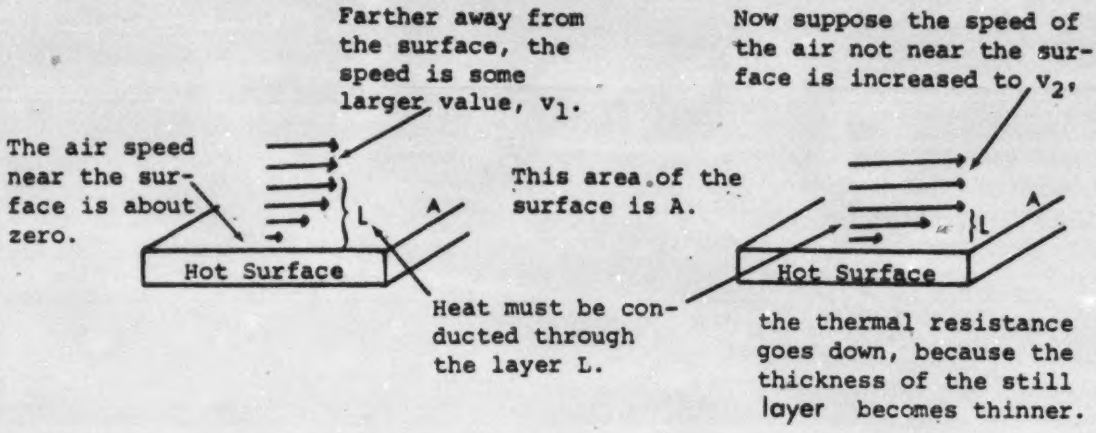
CONVECTION:

A DEFINITION OF CONVECTION

Convection is the process in which heat is carried away by a moving fluid such as air or water. Mass is transferred along with the thermal energy that the mass contains. A moving fluid absorbs energy from any hot surfaces it passes, and then carries away this absorbed energy as part of its own internal thermal energy.

SOLVING THE AIR PROBLEM

In conduction, air is important because a thin layer of air gets heated by the hot surface of, say, the transistor. In equilibrium, the heat must flow out through the warm layer before it is completely dissipated. (If it didn't, the air would heat up more, which is transient behavior). But air is a fluid, and can be easily moved. Therefore, why can't we just blow all the hot air away, and make the resistance of the air become zero by removing the hot layer of air? (That is, since $R = L/kA$; making $L = 0$ means $R = 0$.) This is what convection begins to do, but it can't do it perfectly because fluids "stick" to surfaces (see the illustration). However, when the air flows faster the layer of nearly still air gets thinner, and thus the heated layer gets thinner. These two layers are not exactly the same thickness, but the thicknesses are roughly proportional to each other.


Farther away from the surface, the speed is some larger value, v_1.
Now suppose the speed of the air not near the surface is increased to v_2.
The air speed near the surface is about zero.
This area of the surface is A.
L
A
Hot Surface
Heat must be conducted through the layer L.
the thermal resistance goes down, because the thickness of the still layer becomes thinner.

In convection, a moving fluid carries away heat. Convection also involves conduction, since before being carried away, the heat must pass through the layer of nearly still fluid near the surface. The thermal resistance is approximately $B/(\sqrt{v}\,k\,A)$, *where k is the conductivity of the fluid, A is the surface area, v is the "far away" velocity, and B is a constant which depends on the fluid.*

THERMAL RESISTANCE AND CONVECTION

The thickness of the layer of fluid through which heat must be conducted is roughly given by

$$L = B/\sqrt{v}\ ,$$

where v is the velocity of the fluid outside the slow air layer, and B is a constant that depends on the properties of the fluid, such as its specific heat and "viscosity."

Using this relation for L, and putting it into the power equation for conduction:

$$P_{cond} = \frac{kA}{L}(T_2 - T_1)$$

...we get the power equation for convection:

$$P_{conv} = \frac{kA\sqrt{v}}{B}(T_2 - T_1)$$

from which we can write down:

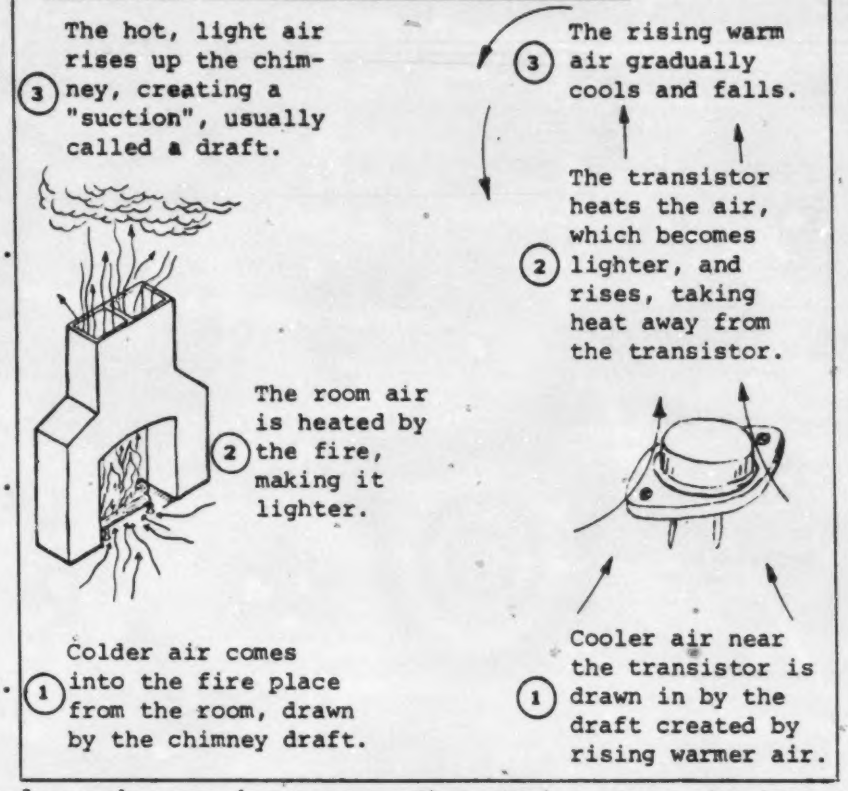
The Thermal Resistance for Convection $\quad R_{conv} = B\left(\frac{1}{\sqrt{v}}\right)\left(\frac{1}{kA}\right).$

The things we have the most control over in this formula are v, A, and k. In experiment II you saw how moving the fan away from the transistor, thus lowering v, raised R. Adding a heat sink made the fan much more effective in lowering R by raising A as was shown in experiment IV. Finally, the easiest way to change k is to use water as the convecting fluid, as is done in car engines, as well as in the most effective heat sinks.

NATURAL CONVECTION

Actually, even in experiment I convection was important. When the air was heated, it became lighter because it expanded, making its density decrease. With a smaller density it floated up away from the transistor. At the same time cool air came in to replace the warm air, thus creating a small "wind". This "wind" gets faster as the temperature goes up. Thus R_{conv} will decrease somewhat as the transistor temperature gets higher. In a fireplace this process is quite visible, at least wherever the smoke and sparks can be seen. The same process is important in the atmosphere: the air is heated by the earth in some spots more than in others. The warmer air rises, cooling down (mostly due to expansion) as it goes.

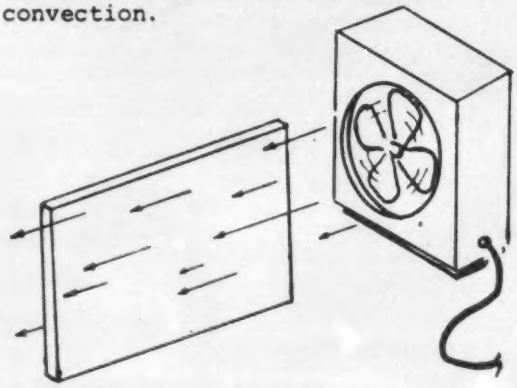
Two Examples Of Natural Convection:


3 The hot, light air rises up the chimney, creating a "suction", usually called a draft.
2 The room air is heated by the fire, making it lighter.
1 Colder air comes into the fire place from the room, drawn by the chimney draft.
3 The rising warm air gradually cools and falls.
2 The transistor heats the air, which becomes lighter, and rises, taking heat away from the transistor.
1 Cooler air near the transistor is drawn in by the draft created by rising warmer air.

FORCED CONVECTION

The fluid velocities in natural convection are so small that they are quite hard to detect over the transistor. It is possible to tell that the air is warmer above the transistor than beside it, but that is about all. A fan which forces air to move by at much higher fluid velocities lowers the thermal resistance, as can be seen in the formula for R. The graphs on the next page show typical

The difference between natural and forced convection is that in forced convection a fan or pump is used to move the fluid, instead of relying on temperature differences as in natural convection.



Forced convection gives greater fluid speeds, and thus lower thermal resistance than natural convection.

data on a heat sink similar to the one you used. The thermal resistance is seen to decrease considerably as the forced air velocity increases. The variation shown is almost exactly that given by the expression for the thermal resistance for convection, it is proportional to (a) $\frac{1}{\sqrt{v}}$:

$$R_{conv} \propto \frac{1}{\sqrt{v}}$$

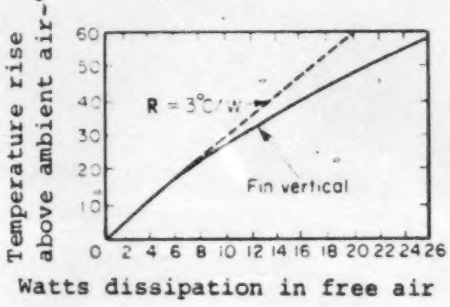
If water were circulated at the same velocities as those shown for air, the cooling would be even greater due to the fact that water has a considerably better thermal conductivity than air. However the complications of a closed water circulatory system and a pump would have to be weighed against the improved heat dissipation.

Thermal Characteristics of a Motorola MC-10 heat sink.

Specifications

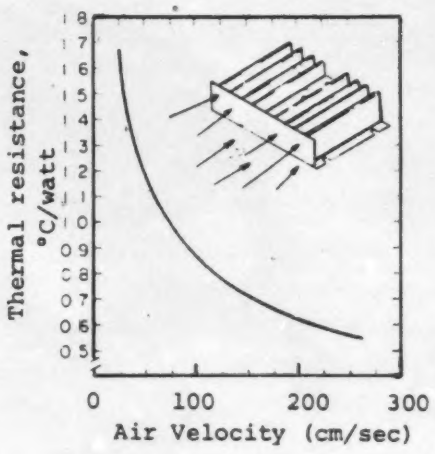
Material	Aluminum alloy
Finish	Black
Total surface area	65 sq in (approx)
Thermal resistance	3°C/watt

NATURAL CONVECITON



Under natural convection the amount of heat dissipated increases with the temperature difference between the sink and the air. The thermal resistance, R, the slope of the curve, decreases slightly as T goes up because natural convection and radiation becomes more efficient at higher temperatures.

FORCED CONVECTION



Under forced convection the thermal resistance is seen to decrease rapidly as the velocity, v, of air flow increases. According to the relation R varies as $\frac{1}{\sqrt{v}}$ *, which is almost exactly the equation of the curve shown.*

A DEFINITION OF RADIATION

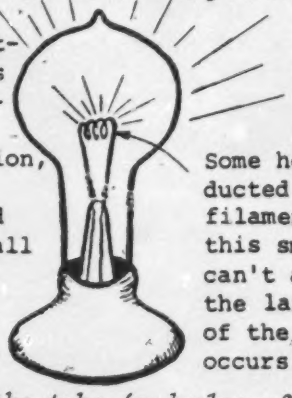
Radiation is the process in which energy is transferred in the form of a wave motion. In the case of a vibrating loudspeaker, the radiation is in the form of sound waves. In most cases important in heat transfer, the waves are *electromagnetic* ones, such as visible light or infra-red radiation.

WHAT IF THERE WASN'T ANY AIR?

If there were no air around the transistor, conduction could get heat to the surface of the case, but there would be no way for conduction or convection to take the heat away. Does this mean that the thermal resistance would be infinite and the transistor would go on heating up until it burned out? In fact, it would, if there were no other processes at work. However, we know that old style light bulbs and vacuum tubes get quite hot to the touch, even though there is very little air in them. The fact that a glowing wire is present in each of these cases is a clue to the reason for the heating - energy can be transferred as light or other invisible forms of *radiation* such as infrared, or ultra-violet radiation. It would take a rather long story to explain what this radiation is in more detail - for the moment a reasonable definition is that it is a form of wave motion which carries electromagnetic energy from place to place, even through "empty" space.

In a vacuum tube or in an older style light bulb, there is no gas to conduct or convect heat from the filament to the glass.

Most of the heating of the glass is due to *radiation*. Electromagnetic radiation, such as light, radio waves, and infra-red rays all carry energy.



Some heat is conducted throught the filament wires, but this small amount can't account for the large heating of the glass that occurs.

In the case of the tube (and also of the power transistor) the radiant energy is mainly in the form of invisible infra-red radiation, which is stopped by the glass and results in heating. The visible light mainly passes through the glass and does not heat it.

RADIATION AND THERMAL RESISTANCE

It is even more difficult to compute thermal resistance for radiation than it is for convection. To get some idea of what factors are important, the following formula for the radiated power is useful:

$$P_r = \varepsilon\sigma T^3 A(\Delta T)$$

where T is the temperature in degrees Kelvin ($T(°K) = T(°C) + 273$), σ is a constant, ε is the "emissivity" which depends on the properties of the radiating body, A is the area of the radiating surface, and (ΔT) is the temperature difference between the body and the surroundings. Comparing this expression to that for power implies that

The thermal resistance for radiation $R = \dfrac{1}{\varepsilon\sigma T^3 A}$

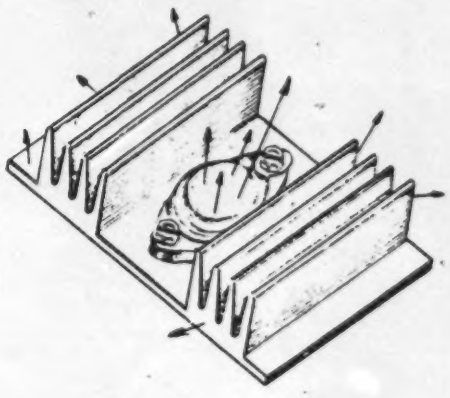
The number ε is always between 0 and 1. When it is 1, the body is called a *black* body, because it looks black at room temperature; a perfect black body is the most efficient radiator. (This does not

imply that all things that look black are black bodies, since they may be "unblack" outside the visible range of radiation.)

USING THE RESISTANCE FORMULA:

How does this formula help us? First of all it says that, as with other heat transfer processes, when the area goes up (by adding a heat sink for instance) the thermal resistance for radiation goes down. Secondly, as the temperature goes up, the radiated power goes up: one reason why light bulb filaments have to be so hot is to generate enough radiated power. Thirdly, increasing ε lowers the thermal resistance. This can be done by painting the radiating body (for instance the transistor or heat sink) black.

In the transistor experiments you performed, radiation isn't too important. (It was of greater importance in experiment IV than in any of the others.) However, many heat sinks are black, since the extra lowering of thermal resistance due to this is useful in some situations.



Even if an object is not in contact with anything else, energy is transferred by radiation.

SUMMARY CHART: How to Change R for the Three Heat Transfer Processes

The chart below indicates how to decrease R, making the heat transfer more efficient. To increase R, simply do the opposite of the indicated method for decreasing R.

Process	Rate of Heat Transfer	Thermal Resistance	What we can do to decrease R
Conduction	$P = \frac{kA}{L}\Delta T$	$\frac{L}{kA}$	* make conduction path L small * choose materials of high conductivity k * make cross-sectional area A large
Convection	$P = \frac{\sqrt{v}kA\Delta T}{B}$	$\frac{B}{\sqrt{v}\,kA}$	* provide for good circulation of some fluid * increase the fluid velocity * have large area A for contact between fluid and material * use water instead of air
Radiation	$P = \sigma\varepsilon AT_{av}^{3}\Delta T$	$\frac{1}{\sigma\varepsilon AT_{av}^{3}}$	* choose materials of large emissivity ε * paint the surface black to increase ε * have a large surface area A * have a high temperature

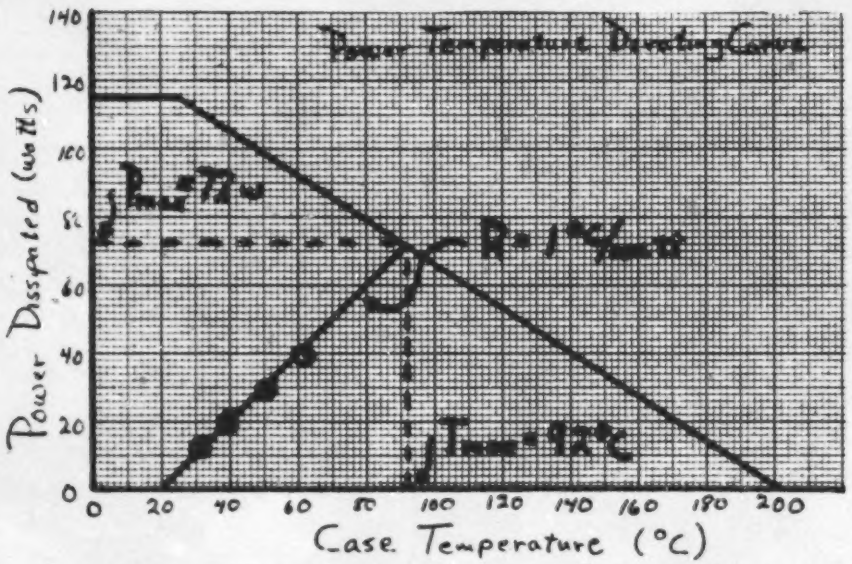
USING THERMAL RESISTANCE..

INTRODUCTION

The last few pages have described what thermal resistance depends on, and how these factors can be used to improve the heat dissipation of a power transistor. In what follows, you will read about a number of other applications of thermal resistance. The first of these is also directly useful in the case of the power transistor.

USING YOUR DATA: Maximum Transistor Power

You can use your data from the experiments of this section (particularly experiment II) along with the derating curve from Part II to predict the maximum power that the transistor can handle without burning out for a given setup. The following steps will help you do this:



1. MAKE A GRAPH of the power derating curve shown in Part II on an 8½ × 11 piece of graph paper. This graph gives the maximum power for the transistor for a given case temperature.

2. PLOT THE POINTS you found in experiment II for T_f and P using your actual T_f values.

3. CONNECT THE POINTS with a smooth curve (it should be nearly straight).

Note that for P = 0, $T_f = T_{air}$ is one point, and thus only one other data point is needed if you assume the graph is a straight line. Nonetheless, plot all the points that you took to see how straight they lie. The derating curve will cross the P,T curve at some point.

4. FIND THE POWER AND TEMPERATURE for this point where the graphs cross. These are the *maximum power* and *case temperature* the transistor can take for this situation. Any higher power would yield a temperature above the transistor ratings.

5. FIND THE MAXIMUM POWER FOR OTHER R'S. Having done this once, you should now be able to use this method to find the maximum power for other situations, knowing only T_{air} and R since this allows you to predict T_f. Try this for the other experiments of this section. Put all the graphs on the same piece of graph paper. Check particularly to see if the $P_{max} = 8$ watts value given in Part I for the transistor alone agrees with your data. Be sure to label each curve.

THINK ABOUT YOUR DATA

Here are some questions to help you understand your data in terms of the graphs you have just drawn.

* Which situation gives the maximum safe power input? Why is it the best?
* What would the graph look like (approximately) if, in the case that gave the greatest allowed power, you painted the heat sink black as well?
* How much did placing the piece of cardboard over the heat sink affect the maximum safe power? Which heat transfer process did it influence most?
* Which heat transfer process seems to be the most effective in raising the safe power limit?

APPLICATION OF HEAT TRANSFER PHYSICS –
WHERE IS EACH PROCESS IMPORTANT?

INTRODUCTION

The last few pages have described the details of three major heat transfer processes - conduction, convection, and radiation. It is often useful to know in what situations each of these processes is most important. As a general rule, a greater amount of heat is transferred from or to an object when its area is increased or when the temperature difference between it and its surroundings increases. This is true for each of the heat transfer processes. Thus, the fins on the heat sink improve the rate of heat loss from the transistor by conduction, convection, and radiation, by increasing the area of the sink.

Other examples of where a given process will be most important are given below.

CONDUCTION:

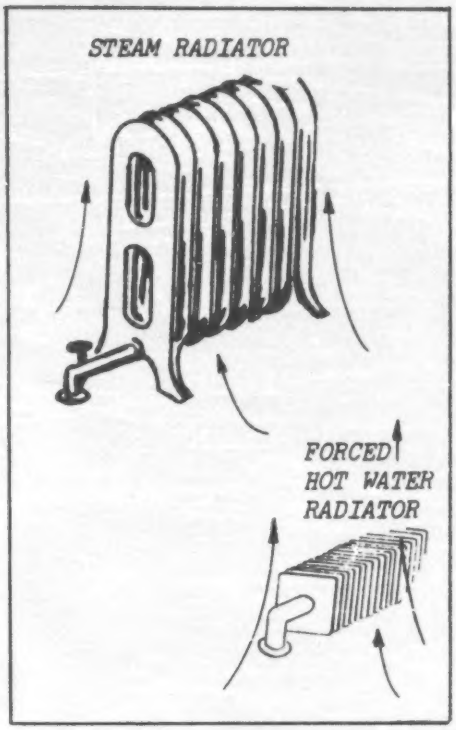
The best thermal conductors are the same things that are the best electrical conductors, namely metals. Thus, heat flow by conduction is most efficient when metals provide a path for the heat. Water is a fairly good thermal conductor, as are most liquids, but not nearly as good as most metals.

One of the best thermal insulators is air. Few other substances have as low a thermal concutivity as it does. Because of this, the warmest winter coats are ones which keep a large amount of still air "trapped" in them, thus keeping the wearer well insulated. (It is important that the air is kept still, since that keeps convection from occurring.) The still air in between a regular window and a storm window is a large part of why storm windows are useful in keeping a house warm.

CONVECTION:

Wherever there is a moving fluid (air, water, etc.) convective heating and cooling occur. Water is a better convective coolant than air, but as you saw in the experiments, air still can be quite effective. Both substances are used for house heating systems. In the case of a hot air system, air is heated and then blown into the rooms of the house. When hot water is used, the water is pumped through metal pipes which have a good conductivity. The thermal energy in the water is conducted through the pipe walls and into metal fins in the room radiator, where the natural convection currents in the room carry away the heat, thus keeping the room warm.

Convection becomes particularly important when evaporation or condensation takes place. When the perspiration of our skin evaporates, it uses a fairly great amount of energy to turn from a liquid (water) to a gas (water vapor). The energy that is taken away in this process cools the body. A wind greatly increases the evaporation rate, and thus keeps the body cooler. This is why a breeze is so welcome on a hot summer day - the convective cooling done by the air is made much more effective by the evaporation of water. The reverse process occurs in steam and forced hot water radiators. Hot steam or water is carried ("convected") into a radiator where it releases its energy, heating the metal it condenses on. This heat is then conducted and convected into the room.



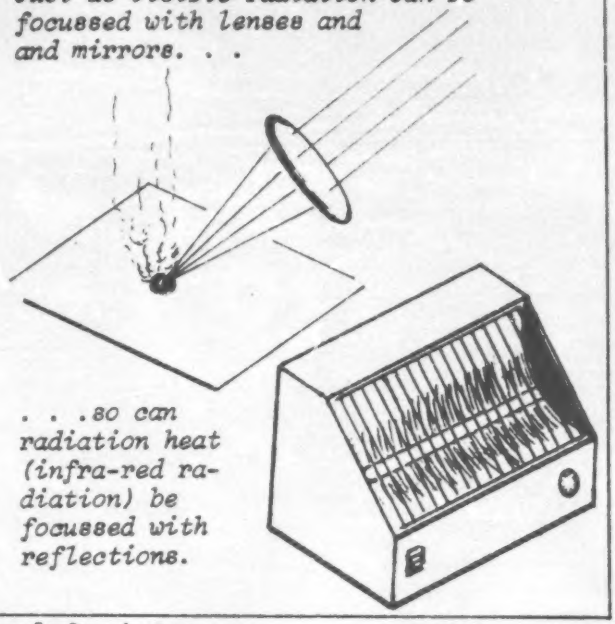
RADIATION:

One case where radiation is very important is when a body is glowing hot, that is, when it is hot enough to give off light. The earth receives most of its energy by radiation from one such glowing body - the sun. Electric heaters are often made for heating rooms or ovens or toasters by making a piece of metal glow red hot due to a current flowing in it. Much of the heat thus generated is transferred to the surroundings by radiation.

Radiation is important in a number of cases where nothing is "glowing" however. One example of this is the case of power transistors, where radiation is not usually the major heat transfer process, but where it can be important.

Another case where radiation is important is when something at a different temperature from its surroundings is in a vacuum. The only way it can dissipate heat is by radiation. This is the case for filaments in vacuum tubes, and for the sun and planets in space. If the earth didn't dissipate as much energy as it receives, it would heat up and become too hot for life to exist on it, and the only way it can dissipate heat is by radiation.

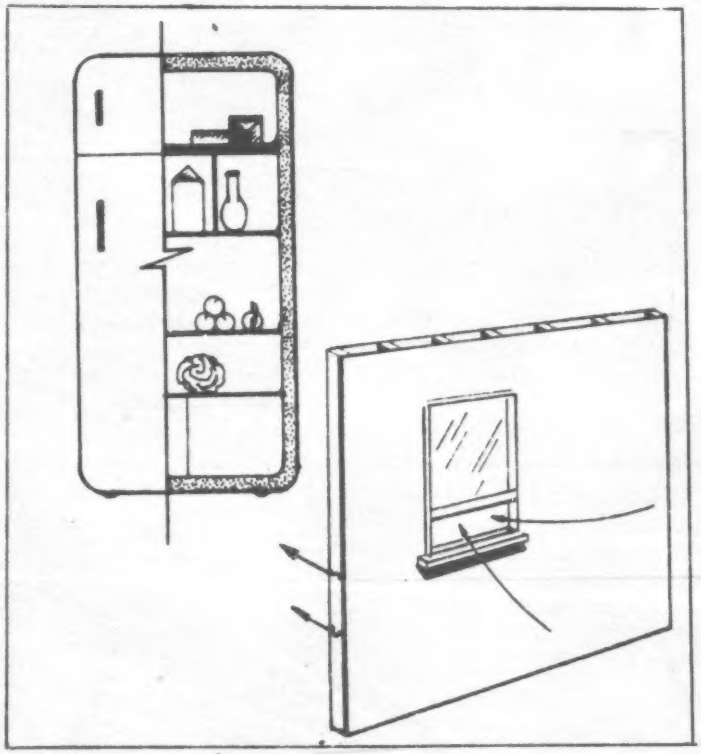
Reflectors and lenses are sometimes used to redirect or focus radiant energy. Many toasters and room heaters have reflectors to make energy flow in the desired direction. The sun can be focused with lenses to make one spot become very hot. Reflectors can also be used as radiation shields; one way to keep a house cooler in the summer would be to cover the roof with shiny reflecting metal. Thermometers used to measure air temperature are sometimes shielded from the sun's direct rays by a piece of metal which reflects much of the incoming radiation.


Just as visible radiation can be focussed with lenses and and mirrors. . .
. . .so can radiation heat (infra-red radiation) be focussed with reflections.

INSULATING: - Increasing the Thermal Resistance

Often it is useful to "thermally isolate" a system from its surroundings. That is, in many cases it would be nice to keep all or most of the heat from flowing out of a region or body. In the winter, people try to keep themselves insulated from the cold air by cutting down on conduction and, more importantly, convection by wearing heavy clothes. What this means in the terms of this module is that the thermal resistance between the person and the air is made higher by jackets and other warm clothing.

In the case of the refrigerator, we want to keep thermal energy from flowing from the room to the inside where the food is to be kept cool. This is done by using thick walls that won't allow air to flow through them, and which have a low thermal conductivity. The walls of buildings are usually made with some of the traits of refrigerator walls, but here there are new limitations due to the fact that people like to see outside, and that they need to breathe. Because of this, house walls must not be air tight, and they must have windows in them. Thus they aren't as good insulators as refrigerator walls.



Review

SUMMARY

The three main heat transfer processes are *conduction*, *convection*, and *radiation*.

Conduction is the process in which thermal energy only is transferred through a body or a fluid, but no mass is transferred. Conduction is most important where metals are present, but it is also important at other times, particularly since convection depends on it.

Convection is the process in which *heat is carried away* by a *moving* fluid, such as moving air or water. Nearly everywhere a fluid flows, convection occurs. It becomes particularly important when the fluid motion is forced to be fast, or when *evaporation* (or condensation) takes place.

Radiation is the process in which energy is transferred by *wave motion* - in particular *electromagnetic* waves which can travel through regions where no matter is present. Wherever glowing bodies are present, radiation is important, but even if things aren't glowing, they may still be giving off a large amount of invisible infra-red radiation.

The experiments of this section showed how to increase the amount of heat transferred away from (dissipated by) the transistor:

A *heat sink increases the surface area* and this aids all the transfer processes. It has fins to make its area even larger, and many heat sinks are black to increase radiation.

A fan makes air move faster, thus increasing the convective cooling.

Another result of the experiments was to show that thermal resistance depends fairly little on temperature, and thus it can be used to predict the maximum operating input power with the help of the power derating curve.

A third result of the experiments was to show that not all heating and cooling is exponential. Nevertheless, such terms as "response time" are used to indicate how long the transients are for a particular system.

The ideas of heat transfer are useful in understanding a number of things - from why we wear winter jackets, to how big an air conditioner we need in the summer.

QUESTIONS

1. There are other kinds of resistance that are useful in applying physics to various situations. You are probably familiar with *electrical* resistance, which enters into Ohm's law

$$I = \frac{V}{R} .$$

In this equation, the electrical current is analogous to the "heat current," P_d, and the potential difference V is

analogous to the temperature difference $T - T_{surroundings}$. Another kind of resistance (fluid resistance) is used to describe the flow of liquids in tubes,

$$v = \left(\frac{1}{R_f}\right)(P_1 - P_2).$$

What this equation says is that the velocity, v, of a fluid in a pipe is a constant times the difference in pressure between the two ends of the pipe.

a) Using this, what is R_f for a pipe which requires a pressure difference of 200 nt/m^2 to maintain a velocity of 15 m/sec?

b) What do you think would happen to R_f if the pipe were twice as long? if the pipe had twice the diameter?

2. Suppose it was 5°C outside (check that this is 41°F) near a river also at 5°C. In the air on this day, the temperature of a brave-hearted person's skin was maintained at 30°C by the heat generated by the chemical reactions in his body. Further suppose that this person decided to go swimming.

   a) If the heat he generates stays constant, what happens to his skin temperature?

   b) If the thermal resistance from his skin to the surroundings changes by a factor of 10 (which way?), what would his final skin temperature be?

   c) When this brave soul got out of the water, would his thermal resistance to the air be the same as before? If not, what has changed, and would his skin temperature be higher or lower than it was before he went swimming?

   d) What heat transfer processes are most important in each of the above situations?

3. Describe all the ways you can think of that the basic heat transfer processes operate when a light bulb heats the air in a room. (Modern incandescent lamps contain some gas; they used to be evacuated.)

4. What is the most efficient process for dissipating heat in each of the experiments in Part III? What could be done to lower the thermal resistance below the value you found in experiment IV?

PROBLEMS

1. a) Look at the transistor specification sheet. What is the thermal resistance between the junction and the case?*

*This value will vary from as much as 0.5°C/watt for high power transistors to 500°C/watt in low power types.

b) What is the principal contributor to this thermal resistance?

c) Determine the slope of the Power Temperature Derating Curve from the specification sheet. How does this value compare with the Derating Factor in the Maximum Ratings?

d) Calculate the inverse of the Derating Factor and compare it to the junction-case thermal resistance. What do you conclude?

2. In the Power Temperature Derating Curve the maximum temperature given is 200°C. This indicates the maximum temperature that can be tolerated in the transistor junction. For silicon, your transistor, this is 200°C; for germanium it is more like 100°C. As in electrical circuits, the values of thermal resistance add, so that one may write an expression for the junction temperature (T_j) as a function of power input:

$$T_j = T_{air} + (R_{jc} + R_{ca})P$$

Calculate the value of the maximum power you can dissipate in the transistor without exceeding T_j = 200°C for each case using your data for R_{ca}.

Compare the results of this method to the graphical method suggested in the text.

3. What is the thermal resistance of a square window pane (length of side = 0.75 m), which has a thickness of 0.2 cm? The conductivity of glass is 0.01 watt/cm°C

4. Is the curve at the bottom of the page an exponential? (Check τ, 3τ points.) What is the response time for a system which is heated up this way with a constant power input?